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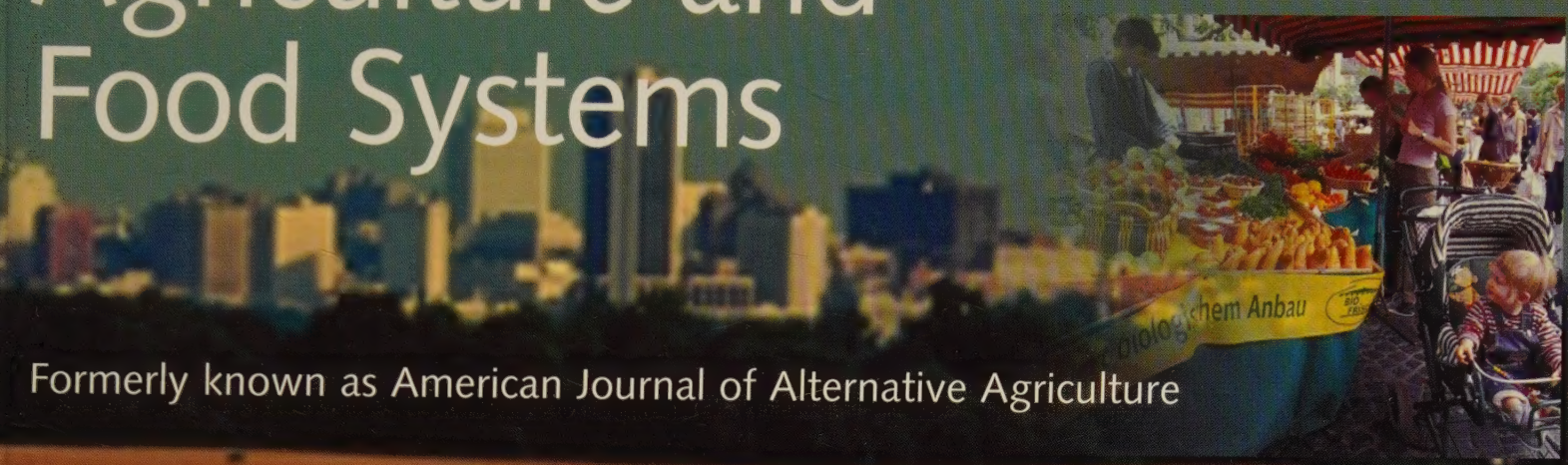

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Renewable Agriculture and Food Systems provides an international forum for original research and review articles on the biological, physical, social science, and policy aspects of alternative agriculture and food systems, focusing on the effective use of renewable resources and biodiversity in agro-ecosystems. The journal particularly welcomes multidisciplinary, holistic, systems research that addresses the multiple challenge of economically meeting basic human needs for food, fiber, and energy while maintaining essential natural and environmental resources.

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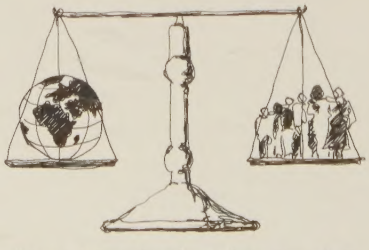

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Phytotoxicity factors and herbicide contamination in relation to compost quality management practices

T. Craig Blewett[1,*], David W. Roberts[1], and William F. Brinton[2]

[1]Dow AgroSciences, 9330 Zionsville Rd, Indianapolis, IN 46077, USA.
[2]Woods End Research Laboratory, PO Box 297, 290 Belgrade Road, Mt. Vernon, ME 04352, USA.
*Corresponding author: tcblewett@dow.com

Accepted 28 November 2004 **Review Article**

Abstract

The practice of composting mixed green wastes from community collection programs has been on the increase as a means to reduce organic debris to landfills. Recent reports of plant injury have appeared and were attributed to residues of the herbicide clopyralid in compost. Phytotoxicity issues with compost have been reported previously to result from other factors, including heavy metal content, soluble salts, organic acids and oxygen deprivation related to incomplete decomposition. The recent reports of plant injury due to clopyralid-contaminated compost were also associated with very heavy applications of compost, yet few of these reports included observations of herbicide symptomology. Since immature compost may contain sufficient degradation intermediates, soluble salts and other contaminants to cause phytotoxicity, particularly when applied at heavy rates, an effort must be made to distinguish confounding factors. Complete composting normally allows for the degradation of phytotoxic intermediates and synthetic compounds, such as herbicides, as well as allowing for leaching of salts. Absence of compost completeness standards within the compost industry leaves such factors to the guesswork of the end-user. Recommended compost use rates have established a relationship between compost maturity, application rate and use pattern, based on compost quality metrics. Greater attention to the use of high-quality compost, properly designated as to completeness of composting and applied at appropriate use rates, would minimize the potential for phytotoxic effects, irrespective of the contributing source.

Key words: compost, clopyralid, herbicide, contamination, immaturity

Introduction

Composting of mixed green-waste collection is on the increase worldwide, as societies attempt to divert biodegradable, recyclable organic wastes from landfills back into agriculture[1]. In 2000–2001 there were two noted incidents in the US where plant injury appeared to have resulted from the use of compost contaminated with clopyralid, an auxin (plant hormone) herbicide[2]. These events received very broad press attention and triggered concerns, which were later put aside, that organic growers could lose certification by using contaminated compost[3]. Clopyralid is thought to have entered the composting stream as residues in home-owner turf grass clippings and ornamental plant leaves, despite precautions on the product labels. High compost application rates were common to both of these locations where the apparent damage occurred[2,4]. In one instance a greenhouse grower transplanted tomato seedlings into 100% compost. In the other incident, an application of 3 inches (7.5 cm) of compost was made in a 'high-tunnel' system, which resembles a greenhouse, where plants are grown on raised beds in the underlying compost–soil blend. In the latter case, clopyralid symptomology was transient, in that the plants outgrew the effects. Salinity stress and oversupply of nutrients were later implicated as complicating yield-reducing factors in the high-tunnel situation[4].

There have been a limited number of additional reports of residential gardens experiencing auxinic symptomology, which clopyralid and phenoxy-type herbicides would elicit, when compost was used. During their follow-up investigation to the greenhouse tomato incident, Washington State Department of Agriculture Inspectors noted that many residential vegetable gardens reported as having possible herbicide damage exhibited poor plant growth, commonly observing stunted plants, but rarely observing any auxinic response[2]. In these poor-performing gardens compost had

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universally been used at very high rates, with plants often grown in virtually straight compost laying on the surface of the soil. The lack of auxinic symptomology in these particular gardens eliminates clopyralid- or phenoxy-type herbicides as a causal agent, implying that other phytotoxic agents were present. The question arose as to what other factors in compost could induce poor performance, whether or not such factors could be mistaken for, or trigger, confounding effects related to herbicide damage.

Compost Quality and Management

Compost is the product resulting from the controlled biological decomposition of organic material, and is presumed to have been sanitized through the generation of heat and stabilized to the point that it is beneficial to plant growth[5,6]. With reports of heavy compost application associated with poor-performing gardens, a review of compost use guidelines is appropriate in the context of reported herbicide contamination. Furthermore, whereas standards for completeness of composting exist in most European countries, few similar standards have been established in the US[7,8]. This fact is pertinent, as it has a bearing on the quality of plant growth from compost in two respects: xenobiotic (exogenous compounds) effects resulting from incomplete biodegradation related to short-term composting, and biological effects related to immaturity[9]. In the absence of compost completion standards, it is not unreasonable to assume that xenobiotics or other phytotoxic agents may potentially present a problem at one point in time or another. The common belief that a contaminant is strictly the problem of the compost ingredient source rather than the composting process is challenged here. Previously, deliberate composting of pesticide residues has been well received, the only difference being that the contamination was known at the outset, and a maturity-based outcome was specified for safe use of the end-product[10]. Thus there appears to be a basis for several confounding circumstances related to plants expressing injury symptoms, depending on compost quality, compost age or maturity, application rate and the presence of phytotoxic xenobiotics.

Many growers report that they do not use compost, owing to uncertainty about its properties[11]. This is supported by concern that many commercial composts are of low to mediocre quality[12]. A very recent survey of 409 organic growers indicated that compost use rate is low due to concerns about poor quality[13]. An examination of the professional growing media industry in the UK indicated that compost usage or substitution of compost for peat is low and is declining due to inconsistency of compost products[14]. A compost use survey conducted recently in Switzerland, covering a 10-year period prior to 2002, concluded that compost sales into horticultural and gardening markets have steadily declined, while use of bulk compost in field farming has increased, partly due to quality problems with regard to higher-value markets[15].

The importance of educating the consumer on health, safety and environmental concerns with respect to compost use has been noted for nearly a decade[16]. The 503 regulations of the US Environmental Protection Agency (USEPA), and some state-specific regulations, have addressed basic safety and environmental issues[17], but may inadequately address horticultural issues. The EPA's 503 rule limits application rates of biosolids (sludge), and composts made from biosolids, based primarily on heavy metal content. The rule incorporates the concept of risk-pathways to limit heavy metal application on an annual, as well as a cumulative, basis. However, the EPA 503 rule also requires that biosolids-derived products be applied at no greater than reasonable fertilizer rates for the anticipated crop, based on nitrogen needs. This rule has been widely applied in the US as a regulatory structure at the state level for most types of composting[18], and the pathogen reduction portion was carried forth into the USDA NOP (National Organic Program) compost guidelines[19]. Furthermore, some states are exercising their right to enforce application rate control at no greater than a phosphorus-fertilizer rate[16] (confirmed by Rufus Chaney, USDA-ARS, Beltsville, MD, personal communication, April 2003) and there has been a general shift towards phosphorus rate control over nitrogen. With certain composts, it has been shown to be impossible to provide sufficient nitrogen for wheat culture without also oversupplying phosphorus, potassium, salts and possibly other hazardous elements[20]. The ratio between nitrogen and phosphorus in compost widens due to N-losses that occur during composting. The overall loss of mass means the phosphorus concentration increases, and thus the nutrient balance, in terms of crop requirements, may be worse in compost, requiring more careful rate control than with raw waste[21]. These findings, overall, demonstrate that it is a well-established fact in environmental management of wastes, and composts in particular, that more than one variable may act to significantly modify application rates where limiting or regulated factors are concerned.

Other compost-related parameters that impact the environment and plant growth have been studied widely, with many countries adopting regulations based on a more refined definition of compost quality[7]. These regulations tie compost quality parameters (as determined by laboratory analysis), such as self-heating, CO_2-respiration and cress (plant growth) tests[22], to certain applications and use rates. In Switzerland, compost cannot be sold for use in horticulture and gardening unless it passes a plant performance test[23]. Under the same rule, compost is only exempted from the requirement to meet a plant toxicity test where the anticipated use is in field farming, since the application rate is assumed to be much lower. In the US, compost other than biosolids is either not regulated at all or is generally not regulated to the same extent as in Europe; although, as has been pointed out, the EPA 503 rule has been widely applied as a general standard for all composts in terms of heavy metal concentration, fecal coliform and salmonella presence. Application of biosolids is also

restricted by nitrogen content, to that expected to be used by the crop grown on that site. High application rates of green-waste or animal manure-based compost can supply on the order of 5600 kg ha^{-1} (5000 lb acre^{-1}) of total nitrogen. Although it is considered that only 7–10% of the total nitrogen is readily available[24,25], annual applications of high rates of compost are likely to eventually supply nitrogen considerably in excess of crop demands. This will result in a significant potential nitrate leaching hazard, among other potentially harmful effects such as those due to salts or other hazardous ingredients[20]. Furthermore, the extent to which agencies and composters may be truly perplexed about the relationship of compost quality to use pattern is seen in the recent AASHTO MP-9 specification[26]. This document sets forth compost test grades to enable products to be applied for erosion and sediment control. A separate evaluation of these standards indicated that virtually all composts, save only feedlot manure compost, would pass the specification to be used on slopes and in berms for runoff control[27]. This is a very surprising development, since leaching of salts, and especially nitrates and phosphates, is likely to result from the heavy rates of some high-analysis products.

Producer-based, government and university publications have been produced for compost users that describe compost quality benchmarks and appropriate uses[6,28–30]. Key factors for objective measurement and reporting include pH, salinity, nutrient content, organic matter content, carbon to nitrogen ratio, heavy metal analysis, maturity, stability and plant growth screening. All of these factors can have a direct influence on the beneficial effects of compost on plants.

Compost is generally recommended as a soil amendment, intended for blending with soil or other matrices. High blending rates (80–100%) of compost have been noted for some potting mixes, but explicit disclaimers or cautions, regarding testing before use, are included[6,16,25,31]. Even with blending for potting mixes, direct seeding into the mixes is not recommended. Rather, blends of 20–30% compost are only recommended for transplanting seedlings[6,25,31–33] (confirmed by Rufus Chaney, USDA-ARS, Beltsville, MD, personal communication, April 2003) that are at least 1 week beyond the cotyledon stage[32].

Salinity and maturity, in particular, are two significant factors in compost quality that can elicit phytotoxicity symptoms. High salinity affects the water relations of the plant, eliciting a range in symptomology from yield reduction[34] to leaf burning[35], leaf deformation[31] and epinasty[35]. These effects can be attributed falsely to herbicide toxicity, especially by untrained individuals. Immature or unstable compost may contain sufficient volatile organic acids, fatty acids, phenolic acids, ammonia or ethylene oxide to elicit stunting and other phytotoxicity symptoms[25,31]. In container-mix studies, it has been demonstrated that immature compost deprives the soil of oxygen content for a significant period of time, resulting in stunting of roots[36].

As a result of the potential for a myriad of innate factors in compost which can cause negative growth effects, research and industry groups have published generalized application rates for compost, which are summarized in Table 1. Clearly, there is a relation between application rates and utilization pattern. Vegetable crops, which likely comprise the most sensitive cropping system, have the lowest recommended use rates, less than 2.5 cm or approximately 147 tonnes ha^{-1} (~15% by volume). The exception to this is use in potting mixes, but use in potting mixes is normally accompanied by explicit precautions on quality assessment, especially in regards to salt content, stability and maturity, as noted above. Some publications are quite emphatic that applications for gardens and field crops should not exceed a 2.5 cm layer or 112 dry tonnes ha^{-1} [37], a rate which, nevertheless, is extremely high from a nutrient management point of view.

Herbicide Contamination

The utilization pattern and rate of application are directly related to the issue of pesticide residues in compost. Recent work has shown that compost containing residues of clopyralid can elicit phytotoxicity symptoms on sensitive species[38]. Results of this work indicated that even sensitive plants were likely to escape damage at relatively high compost application rates (Table 2). Research at Washington State University-Puyallup demonstrated that sensitive plants produced greater biomass even at higher compost application rates where clopyralid was present, by responding to the greater nutrient levels and possibly also organic content provided by the compost[39]. Under these circumstances, it is arguable that any negative effects have occurred at all.

Researchers in California composted cotton gin waste that had residues of insecticides, herbicides (paraquat) and defoliants[40]. Field experiments indicated that germination was inhibited at application rates greater than 11 tonnes ha^{-1} for composted waste and 45 tonnes ha^{-1} for non-composted waste. Rates higher than 17 tonnes ha^{-1} inhibited yields, largely as a result of inhibition of seedling emergence. Composting doubled the salt concentration of the compost and likely contributed to the inhibition of both germination and growth. After 51 days of composting, some pesticides had substantially degraded, and others, while degrading, actually increased in concentration. Similar results, showing an apparent increase in clopyralid concentration, have been observed after a 49-day thermophilic composting period, during which organic matter loss exceeded the rate of clopyralid degradation[41]. However, maintaining favorable curing conditions beyond the 49-day thermophilic period resulted in rapid degradation of clopyralid residues. Work in Canada showed similar results—concentration of pesticide residues in the early stages of composting was followed by a decline—evidence that the organic matter was degraded faster than the pesticide[42]. In the Canadian study, after 10 weeks of

Table 1. Compost blending rates for various utilization patterns.

Compost utilization	Blending rate[1] (% by volume)	Approximate application rate (m^3/ha^{-1})	Approximate application rate (cm-layer)	References
Potting media				
General potting media	33	750	5	6, 25, 31, 32
Containerized bedding plants	20	330	2.5	6, 31, 32
Vegetable transplants (not direct seeding)	20	330	2.5	6, 25, 31, 32
Horticulture				
Ground cover bed/mulching	20–33	220–750	2.5–5	6, 25, 31, 32
Nursery crops (tree and shrubs)	33	750	5	6, 31, 32
Agriculture/horticulture				
Row crops and vegetable crops	5	82	0.61	6, 16, 25, 31
Pasture and hay/legume crops	2	24	0.25	16
Strawberries, blueberries, grapes	15	245	1.88	16
Pumpkins, winter squash	15	245	1.88	16
Turf grass establishment	33	750	5	6, 25
Top soil blend	33	750	5	6, 25
Hydroseeding	Air-blown	120	1.25	[2]

[1] Maximum blending or inclusion rates. When using compost in a specific application for the first time, or when using a specific type or source of compost for the first time, the compost should be tested on a small scale. A soil test is also strongly suggested. All compost products, climatic conditions, crop requirements and field situations are different, and require specific recommendations from experts familiar with those specific field situations. Consultation should be supplied by compost producers and their technical staff, and may also be obtained from agricultural institutions and the Cooperative Extension Service of the USDA. States may have specific regulations regarding compost utilization. State regulations should be consulted concerning maximum allowable application rates for specific situations or crops. Compost suppliers should be able to provide relevant data on these issues. (Above precaution from: the US Compost Council's Field Guide to Compost Use[6].)

[2] Mark Mauer, Washington State Department of Transportation, personal communication, April 2002.

composting, phytotoxicity was still observed from compost made from grass clippings that had been treated with 2,4-D, mecoprop and dicamba. A comprehensive literature review of pesticide degradation in compost showed that most, but not all, pesticides completely degrade during composting, while some increased in concentration[43]. Unfortunately, the review did not contain data on quality indices, such as completeness of composting; it would be valuable to determine the correlation between maturity or other quality indices and the presence of pesticide or xenobiotic residues. Recently the State of New York[5] developed a definition of compost maturity to mean 'the characteristics of a soil conditioning material that render it harmless to the plant grown when used as a topsoil or soil supplement'. Adoption of a maturity-based standard for compost use, as suggested by the New York guidelines, or as implemented in the Swiss standards, should uniformly address phytotoxicity and herbicide residue issues from immature compost. However, industry may be hesitant to accept such maturity standards if the required time frame of composting is thereby increased.

Table 2. Predicted crop damage due to clopyralid in compost applied to soil.

Clopyralid in compost ($\mu g\,kg^{-1}$, dry wt)	10 $\mu g\,kg^{-1}$		50 $\mu g\,kg^{-1}$			200 $\mu g\,kg^{-1}$		
Compost application rate (tonnes ha^{-1})	112	448	22	112	448	22	112	448
Compost application rate (tons $acre^{-1}$)	50	200	10	50	200	10	50	200
Winter wheat	N	N	N	N	N	N	N	N
Garden beet	N	N	N	N	N	N	N	N
Sweet basil	N	N	N	N	N	N	N	N
Japan buckwheat	N	N	N	N	N	N	N	N
Radish	N	N	N	N	N	N	N	N
Cucumber	N	N	N	N	N	N	N	S
Lettuce	N	N	N	N	N	N	N	S
Tomato	N	N	N	N	S	N	S	E
Peas	N	N	N	N	M	N	M	E
Dwarf sunflower	N	N	N	N	M	N	E	E
Red clover	N	S	N	S	M	S	M	E

Ratings: N = none, S = slight, M = moderate, E = extreme. None and slight judged acceptable by independent growers. (Modified after Brinton and Evans[36].)

These results indicate that pesticides can be detected and may be phyto-active throughout the composting process. Previous work has shown that a NOEL (no observable effect level) for herbicide residues can be identified that does not pose a threat to plant growth[38,39,44]. Differences in degradation can be related to inherent differences in the biological metabolism of the compound, but may also be related to the composting process[45,46]. Short-term composting (<60 days) largely consists of the thermophilic phase. Without proper curing (mesophilic phase), the degradation of xenobiotics, including pesticides, may not be sufficiently

complete for all possible utilization patterns, or for compost used at high application rates. Additionally, the importance of the curing phase to the biological maturity of compost cannot be ignored. Critical biological recovery and activity continues during the curing phase, resulting in the reduction of naturally produced phytotoxic agents, and an increase of desirable properties for plant growth, such as neutralized pH and increased available nitrogen. More than token attention (as in merely stockpiling) for this critical curing phase is needed in the overall compost process engineering design.

Conclusion

The observations in Washington State of poor-performing gardens following compost application may be due to the overapplication of immature compost, compost that immobilizes nitrogen, or both. In some instances, sufficient residues of clopyralid or other herbicides may have been present in the compost to elicit auxinic symptomology. Immature compost thus provides at least four avenues for potential phytotoxicity: the natural production of phytotoxic degradation intermediates (e.g., organic acids and phenolic acids); high salt concentration; ammonia build-up; and insufficient time or conditions to allow for adequate decomposition of phytotoxic xenobiotics, such as herbicides. The presence of phytotoxic xenobiotic residues must be viewed in the context of overall phytotoxicity potential that includes those of biotic etiology. The presence of these residues should not be alarming if compost use for any particular application is not consistent with its overall properties.

The prevalence of immature composts is of concern, as it presents problems for gardeners whether herbicide contamination is present or not. Greater attention to pesticide labeling, understanding pesticide degradation in compost as well as soil, and the use of properly matured compost at appropriate use rates would minimize the potential for phytotoxic effects, regardless of their source. Misapplication of compost needs to be more effectively addressed by designing and testing finished compost to meet certain performance criteria for a particular utilization market or range of markets. Additionally, more effective education to the end-user on compost performance test results, as they relate to appropriate application rates for a given utilization pattern, needs to be communicated, either by product labeling or product information leaflet at the point of purchase.

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The use of human waste for peri-urban agriculture in Northern Ghana

O.O. Cofie[1,*], G. Kranjac-Berisavljevic[2], and Pay Drechsel[1]

[1]International Water Management Institute, Sub-Regional Office, Accra, Ghana.
[2]Department of Agricultural Mechanization and Irrigation Technology, University for Development Studies, Tamale, Ghana.
*Corresponding author: o.cofie@cgiar.org

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Abstract

In Ghana, studies on the use of organic materials to increase soil productivity have focused on crop-residue management, use of green and animal manures, and legume cover cropping. Few studies have assessed the use of human waste for agriculture, even though this is widely practiced by farmers in the northern part of the country. This study was carried out to investigate the stakeholders in the use of faecal sludge (FS) for crop production in Tamale and Bolgatanga municipalities in the guinea savanna agroecological zone of Ghana. The aim was to determine the driving factors, constraints and potentials for this practice. Field survey and focus group discussions were carried out among 90 farmers who use FS, and officials of the Municipal Sanitation Unit were interviewed. Sixty-four percent of farmers interviewed used FS as a cost-effective way to improve soil fertility and increase yields of maize and sorghum. Sludge is discharged by spreading it on the soil surface, or it is stored and dried in pits during the dry season and incorporated into the soil at the onset of the rainy season. The high temperatures of the savanna climate and this long period of drying allow sludge to be handled easily. Although this treatment is perceived to reduce the number of pathogens in dried sludge, 22% of farmers complained of itching feet and foot rot after working with FS, which is done without wearing protective foot covering. This constraint is coupled with the foul smell, transport problem and public mockery associated with the use of human waste for agriculture. In spite of these problems, there is competition for FS among farmers, due to benefits derived from its use. Further investigation is required to ascertain the causes of itching feet and foot rot, and there is a need for education on proper handling and appropriate hygiene practices when working with FS. Information regarding optimal FS application rates is also required.

Key words: human waste, faecal sludge, peri-urban agriculture, Ghana

Introduction

Balancing food security and environmental health with increased demand for food and basic infrastructures is of paramount importance in the expanding cities of developing countries. Urbanization in Africa is of the order of 3.5%, three times the rate of rural population growth[1]. Agriculture within and close to the cities could play a major role towards achieving the UN Millennium Development Goal—to reduce the number of people suffering from hunger by half between 1990 and 2015. In addition to supplementing rural agriculture in food supply, agriculture in urban and peri-urban areas creates an avenue for recycling readily available urban wastes, thereby improving the productivity of farming systems as well as environmental health.

In Ghana, as is typical of developing countries, available sanitation facilities are overstretched and human waste management is poor[2]. Sewered excreta disposal systems are rare, due to high costs and scarce water resources. Most sanitation systems for human excreta are on-site facilities, including latrines, non-sewered public toilets and septic tanks. Human waste collected and transported by vacuum trucks to disposal and treatment sites from such on-site installations is commonly referred to as faecal sludge (FS)[3,4]. This type of sludge is highly variable compared to conventional wastewater from sewerage networks, in that it is subject to inconsistent storage duration, temperature and septic tank performance. Since less than 5% of the households in Ghana use sewerage networks, there is significant FS generation.

Although the use of wastewater in agriculture has been well documented in the literature[5–9], direct use of sludge from on-site sanitation systems has not received equal attention. Farmers in China, South-East Asia and parts of

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Africa have used human excreta to fertilize fields and replenish the soil organic fraction[10–13]. Human excreta, like animal manure, is a good soil conditioner and a renewable source of plant nutrients, such as nitrogen, phosphorus and potassium. On a daily basis, each person produces an average of 1.8 liters of excreta, consisting of about 30 g of carbon, 10–12 g of nitrogen, 2 g of phosphorus and 3 g of potassium[6]. The nutrient content of human waste excreted each year is approximately equal to that consumed and to that required for corresponding biomass production[14]. The benefits of using faecal biosolids in agriculture are similar to those for compost. They have been documented by the US Composting Council[15] to include:

- improvement in soil structure, porosity and density, thus creating a better plant root environment; increase in infiltration and permeability of heavy soils, thus reducing erosion and runoff; improvement in water-holding capacity, thus reducing water loss and leaching in sandy soils;
- supply of plant nutrients, as well as significant quantities of organic matter and beneficial microorganisms, to soil and growing media;
- improvement in cation exchange capacity of soils, thus enhancing their ability to hold nutrients for plant use, bind specific pollutants and stabilize pH;
- economic benefits derived from savings in fertilizer cost for the farmer.

In addition to these benefits, there are also potential health consequences associated with FS use. Excreted pathogens—bacteria, viruses, protozoa and helminths (worms)—can be transmitted to humans, thereby causing gastrointestinal and other infections. Two factors, pathogen survival and infective dose, determine whether excreted pathogens are capable of causing disease. The survival rate of pathogens excreted by humans and animals is determined by moisture, pH, temperature and UV light[16,17]. It has been found that worm eggs, such as *Ascaris*, are among the most resistant pathogens in the extra-intestinal environment. The dose required to create disease (infective dose) varies among organisms. For helminths, protozoa and viruses the infective dose is low ($<10^2$), while for bacteria it is medium ($<10^4$) to high ($>10^6$)[6]. While exposure to untreated excreta can cause infection in both field workers and consumers, the thermophilic composting or extended drying of FS can reduce or eliminate the risk of transmission[18].

Agricultural productivity in Ghana

Ghana is a low-income developing country in west Africa, located between latitude 4°44′N and 11°15′N, and within longitudes 3°15′W and 1°12′E, with a total land area of 238,539 km^2. It has a population of about 19 million, an annual population growth rate of 2.7% and population density of 79 persons/km^2 [19]. Urban population is 44% of the total. Administratively, Ghana is divided into ten regions. The Northern, Upper West and Upper East regions constitute the northern sector and form the interior savanna zone of the country.

The mainstay of Ghana's economy is subsistence agriculture. The overall growth rate in the agricultural sector is 2.8%. Ghana's Vision 2020, launched in 1995, targeted an expected annual growth rate of 5–6% for the agricultural sector[20]. However, the Ministry of Food and Agriculture has identified soil fertility decline and soil erosion as major constraints to the desired growth rate. Soils that support agriculture in Ghana developed on thoroughly weathered parent materials that have been leached over a long period of time[21]. As a result, their organic matter content is low. The two most commonly deficient nutrients are N and P, particularly in savanna soils[22]. The build-up of organic matter is further limited by regular burning of crop residues and removal of residues for fuel, animal feed or building purposes[23]. Food supply-and-demand analysis[24] indicates a deficit in the supply of all food items in Ghana. Strategies to increase crop production through the use of chemical fertilizer have been impeded by withdrawal of government subsidies on fertilizer and limited access to credit for farmers. Fertilizer imports declined from 45,000 tonnes in 1990 to 11,000 tonnes in 1994[25], and fertilizer use declined from 4.5 to 2.9 kg ha^{-1} between 1990 and 1996[23].

In Northern Ghana, farmers frequently resort to FS as an alternative to chemical fertilizer. Owusu-Bennoah and Visker[26] reported that 90% of collected night soil in Tamale municipality was used as fertilizer by farmers, although the extent of health and environmental risks involved is not yet documented. The municipal authority frowns at this practice even though no alternative sludge treatment is available. The objective of this study was to assess the farmers using FS as a soil modifier in Northern Ghana, to determine the driving factors, constraints and potentials associated with this practice.

Study Methods

This study was carried out in two municipalities of northern Ghana, Tamale and Bolgatanga, and involved selected farming communities within the municipalities.

Description of the study area

Tamale municipality is the largest in Northern Ghana, with an urban population of about 200,000. Characterized by distinct rainy and dry seasons, the area has a unimodal rainfall pattern with mean annual rainfall of 1000 mm, occurring mainly during August–September (Fig. 1) and a mean annual temperature of around 29°C[27]. In Tamale, where sanitary conditions are generally poor, the average volume of faecal sludge generated annually is 30,607 m^3 [28]. There is no functional treatment facility in the city and no single point for disposal of faecal sludge. Over ten disposal sites are in use around the city, on available land perceived

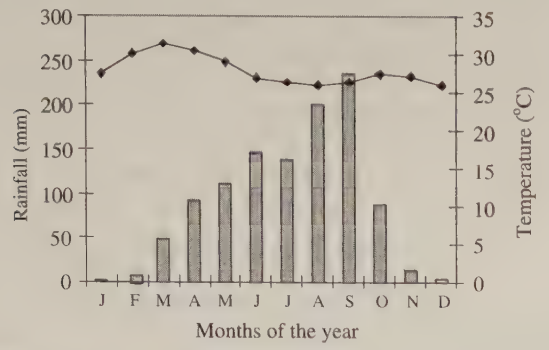

Figure 1. Variation in monthly rainfall (bars) and temperature (line) in Tamale (averages generated from 30 years of climatic data[27]).

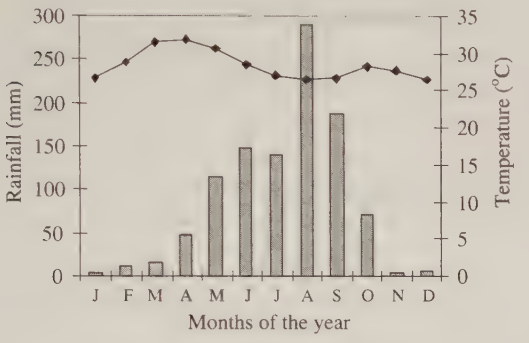

Figure 2. Variation in monthly rainfall (bars) and temperature (line) in Bolgatanga (averages generated from 10 years of climatic data[27]).

to be in a 'convenient' location. A sanitary landfill is currently under construction, but in the meantime FS is discharged onto open lands and nearby streams around the city. Eighty-three percent of the FS generated is collected and disposed of by the Municipal Sanitation Unit, while 17% is disposed of by individual households, particularly those using bucket-type toilet facilities. Toilet facilities are not adequate. A survey conducted in 100 households[29] revealed that 37% had household toilet facilities, such as water closets (15%), ventilated improved pit latrine (6%) and bucket latrines (16%). Fifty-one percent of the surveyed households used public toilets, while the rest (12%) had no confined toilet facilities.

Bolgatanga district has a population of about 228,000, of which 49,000 inhabit the city of Bolgatanga[19]. The rainfall average for 10 years (1993–2002) was 1012 mm per annum, with a peak usually in August (Fig. 2). The average annual temperature is about 28.4°C. The city of Bolgatanga has no treatment plant for processing human faeces. Faecal sludge is collected by the Municipal Sanitation Unit and deposited at a designated site, where it is available to farmers. It is estimated that 426 truckloads, 6.75 m^3 each, are deposited at the designated site annually, making a total of 2876 m^3 of collected sludge. Because a great proportion of human faeces is not collected, actual amounts of FS generated are much greater. However, according to Ghana

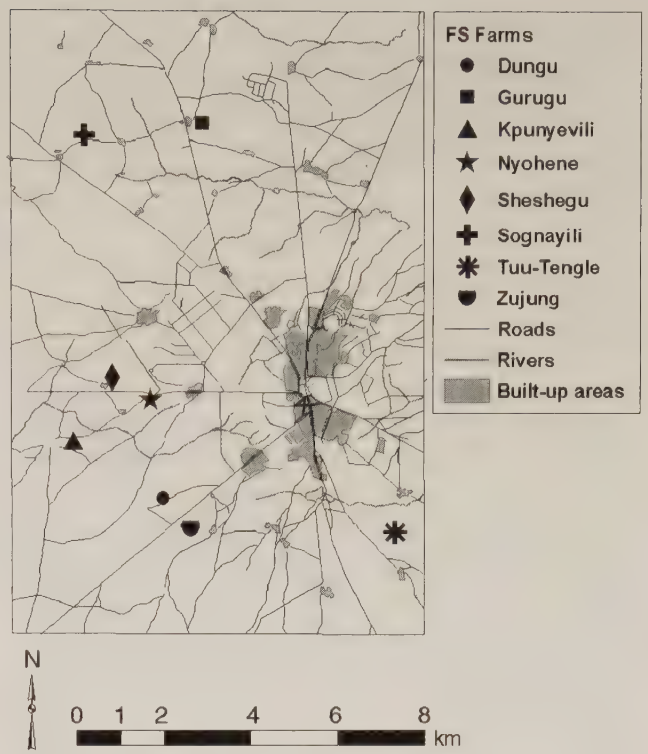

Figure 3. Locations of faecal sludge (FS) farming communities in Tamale municipality.

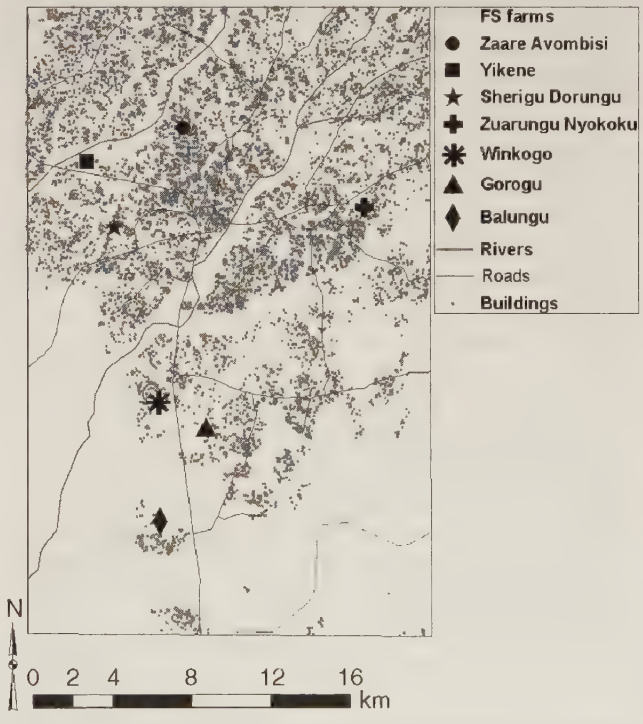

Figure 4. Locations of faecal sludge (FS) farming communities in Bolgatanga municipality.

Statistics Service[19], only 20% of households in Ghana lack access to toilet facilities, from 5% in the Greater Accra Region to 79% in Upper East Region where Bolgatanga is located.

Box 1. Questionnaire

The use of human waste for peri-urban agriculture in Northern Ghana
Questionnaire No.: ..... Community: ..... Interviewer: ..... Date:.....

Particulars of respondents
Name: .....
Sex: .....
Age: .....
Are you a household head? Yes/No
How long have you been farming?.....
Household composition/size. Men: .....Women: .....Children: .....

Farming practices
What is the farming system? .....
What is the land tenure arrangement? .....
Which crops do you cultivate? indicate: Crop.....Plot size.....Yield/plot.....
Who undertakes the following operations (by gender) and for how long?
(i) Land preparation.....; (ii) Planting.....; (iii) Weeding.....; (iv) Faecal sludge management .....; (v) Harvesting.....; (vi) Carting.....; (vii) Marketing.....
What farmers' organizations exist in the community?.....
Do you belong to any farmers' organization? Yes/No
If yes, which one and what is the nature of support you receive from them?.....
What problems do you face in practicing agriculture in/around the municipality?.....
Do you get support for peri-urban agriculture? Yes/No
If yes, indicate form of support for agriculture: Cash.....; Inputs.....; Others.....
Do you use any of these inputs: fertilizer; manure; labor; water; compost; pesticide; farm residue; faecal sludge?
Are the inputs readily available? Yes/No
Do you encounter problems in obtaining them? Yes/No If yes, list: .....
What other employment opportunities exist apart from farming? .....
What proportion of farm yields contribute to household food security? .....
What is the contribution to cash security? .....
List other contributions from farm yields: .....

Faecal sludge (FS) utilization
Why do you use FS? .....
For how long have you been using FS in agriculture? .....
Which type of FS do you use: high strength (public toilet sludge); low strength (septage)?
What are the sources of FS? .....
Is the FS easily available? Yes/No
How long does it take you to receive your requirements of FS? .....
Do you get all your requirements? Yes/No
How much do you pay for FS? .....
How much FS do you apply in your farm? .....
How do you apply (use) the FS in your farm? .....
What has been your farm yield before FS use? (Quantify) .....
What is your current yield with the FS use? (Quantify).....
Are there any social constraints to the use of FS? Yes/No
If yes, name them. .....
Does the food produced using FS pose any health problems? Yes/No
What health hazards does the application of FS give? .....
What are the problems associated with the use of FS in agriculture? .....
What are the benefits you derived from the use of FS? (list) .....

Data collection

Field data were collected in 2002 through interviews and focus group discussions with farmers and Municipal Sanitation Unit officials. There was an initial reconnaissance survey within and around Tamale and Bolgatanga to identify communities using FS (Figs 3 and 4), to promote the study and to pre-test the questionnaire (Box 1). In all,

90 farmers were interviewed. The questionnaire included a list of open-ended questions directed toward farmers, farm characteristics and FS utilization. Data collected were subjected to descriptive statistics using SPSS version 10.

Results and Discussion

General information on respondents

Of the 90 farmers interviewed, 43 were from five farming communities within the Tamale municipal area, while 47 belonged to six farming communities within Bolgantanga. More than half were between 50 and 69 years of age, and they averaged 25 years' farming experience. Ninety-four percent of respondents were male, and female respondents were mainly located in Bolgatanga. Prevailing cultural traditions in Northern Ghana do not favor female ownership of land, which leaves land ownership entirely in the hands of men.

Among surveyed farmers, 84% had acquired their land through inheritance, while the remaining 16% farmed land under hired or borrowed lease agreements, or communal tenure. Hired land indicates release of land by a landowner to another person for a token fee. Borrowed land means that the landowner (usually head of a household) has turned over use of a piece of land to another person without compensation. Both of these agreements may be revoked at any time. Communal tenure is a system of community land ownership that varies from place to place. In the study area, it involves leasing land to a group of individuals living within the same household. Eighty-four percent of surveyed farmers were heads of households, with an average household size of 13 members. Household size is a reflection of the traditional social structure in Northern Ghana, where it is common practice to find extended family members living together.

Farming is the primary source of income for 57% of farmers surveyed and average farm size is 1 ha. Farming systems are dominated by mixed cropping, mixed farming (crop and livestock production) and mono-cropping of cereals. In a few cases, cereals are rotated with legumes, but a majority (74%) of farmers surveyed grow maize, sorghum, millet and vegetables in mixed cropping systems. Both male and female members of households comprise the farm workforce, though their labors are allocated to different farm activities. Men are generally responsible for land preparation (93% of respondents), weeding (76%) and FS management (70%), while women are more involved in planting (50%) and marketing (64%) farm produce. Many farmers indicated that poor soil fertility, crop destruction by animals or bush fires, lack of funds and a shortage of farm land are critical problems (Fig. 5), and that use of FS is a cost-effective means to improve their farm productivity.

Utilization of faecal sludge for cereal production

All sampled farmers use FS for cultivation of cereals, mostly maize, sorghum and millet. Some use other sources

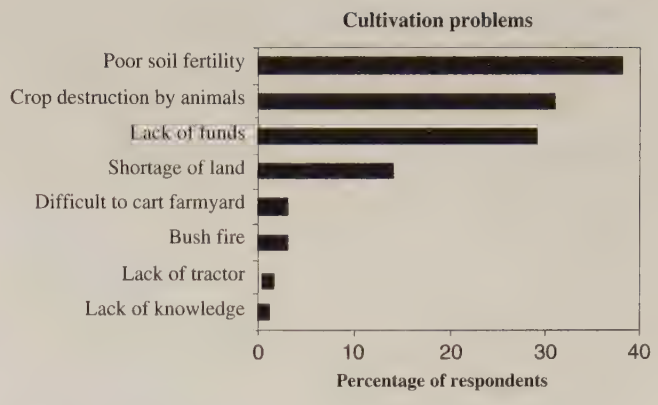

Figure 5. Farmers' description of cultivation problems in Northern Ghana.

of nutrients, such as farm residues (69%), chemical fertilizer (28%), farmyard manure (21%), household refuse (11%) and compost (6%). However, this was not on a regular basis, due to the cost of fertilizer (NPK fertilizer is about $US17 per 50 kg bag), possession of too few animals to generate manure, and the difficulty, as well as labor involved, in transporting and composting farmyard manure. All farmers indicated their preference for FS.

Farmers use different types of sludge, depending on preference and availability. Generally, they prefer stabilized septage from septic tanks. However, as this is not readily available, only 32% of respondents use septage, while the remainder use either unstabilized public toilet sludge or a mixture of septage and public toilet sludge. Although some farmers have used FS for over 30 years, an average of 8 years was recorded. Half of the farmers learned to use FS from their neighbors, but about 10% discovered it through accidental deposition on their farmland by the waste management department. Forty-four percent of farmers indicated that the main reason for using FS is to improve the productive capacity of soil. Other reasons mentioned were to increase crop yield (20%) and to save the expense of inorganic fertilizer (7%). The decision to use FS is based on (often two- or threefold) higher yields of crops grown on FS-treated soils as compared to untreated soils. Moreover, the use of FS involves less labor than is required to collect and compost farmyard manure, and FS is free except for 'tips' given to the truck driver, about $US2 per load of discharged sludge. Twenty-nine percent of respondents did not indicate a reason for using FS.

Methods of cultivation with faecal sludge

Experience acquired over the years has led farmers in Tamale and Bolgatanga to devise specific methods for handling FS for crop production, methods that take advantage of the high temperatures of the savanna climate. They discharge FS on farms during the dry season by one of two means: surface spreading or the 'pit' method.

Table 1. Estimated amount of nutrients applied in faecal sludge by Tamale farmers[1].

Nutrient type	Nutrient concentration (kg)	
	Total (kg m^{-3})	Amount applied (kg ha^{-1})[2]
Nitrogen (N)	8.2	455
Phosphorus (P)	1.1	61
Potassium (K)	2.2	121
Carbon (C)	21.3	1183

[1] Calculated after Drangert[14], based on the nutrient concentration in human faeces per person-year.
[2] Approximately 56 m^3 of raw sludge is applied per ha in Tamale.

Surface spreading. This involves the discharge of faecal sludge at random points (accessible to the septic emptier) within farmers' fields in November. By the end of the season, the discharged FS becomes very dry and is redistributed evenly across fields before cultivation. As shown in Figure 1, the dry season lasts from November through March or April, when temperature and solar radiation are high and relative humidity is low (generally less than 50%, and as low as 5% in January). These conditions allow the sludge to be handled easily when incorporated into the soil. Moreover, health risks associated with the use of FS are reduced since most microorganisms contained in the sludge are killed by prolonged high temperature and low moisture. According to Feachem et al.[16], the survival time of pathogenic bacteria, viruses and protozoa in FS is less than 100 days, significantly less time than the dry season, which lasts between 120 and 150 days. However, helminths can survive for several months.

The 'pit' method. This method for FS application involves the use of large pits containing rice/maize straw or bran at the bottom. Faecal sludge is then poured into the pit, requiring several trips of the emptying truck. Bran and straw are placed between layers of discharged sludge until the pit is full. The pit is left open for several months to compost until the cropping season begins, when the mixture is applied evenly across the field.

The pit method is not as widely used as the surface spreading method because it requires more labor to gather the high quantities of crop residue used in the process. Moreover, more time is required to compost, dry and spread the FS across the farm.

The use of FS for cultivation in Northern Ghana is mostly restricted to cereals, such as maize, sorghum and millet. The harvested parts of these crops do not come into contact with FS-treated soil. Farmers have learned not to use FS for the production of legumes, such as groundnut, as it causes luxurious vegetative growth but poor pod yield.

Nutrients supplied through faecal sludge use in Tamale

Five trips of the suction truck are used to fertilize 1 acre of land (0.4 ha), an average of 55.63 m^3 FS per hectare.

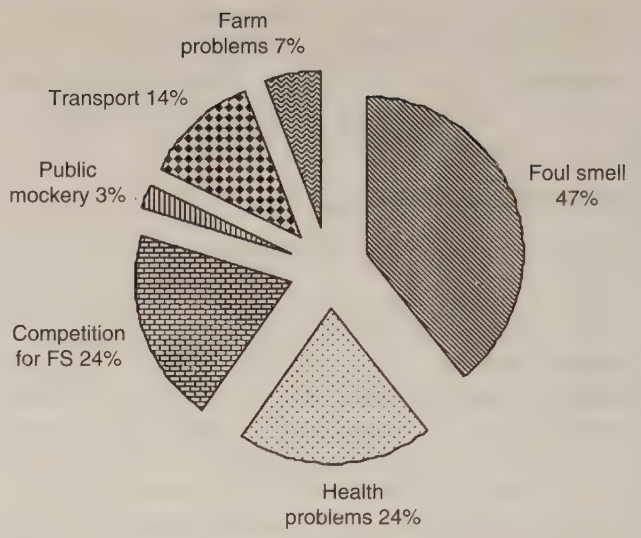

Figure 6. Farmers' description of problems associated with FS application in Tamale and Bolgatanga. The category 'Farm problems' (7%) includes increased weed infestation and labor requirements, the need for protective clothing and potential crop death with excess FS application.

Through this practice, significant amounts of plant nutrients, such as nitrogen (N), phosphorus (P) and potassium (K), are returned to the soil. In addition, the organic matter level of soil gradually increases. Based on the average concentration of nutrients in human excreta, as reported by Drangert[14], estimated amounts of N, P, K and carbon in applied sludge are presented in Table 1. This estimate does not account for nutrient loss during sludge storage in septic tanks or in the field. Considering the current FS application rate by farmers, about 550 ha of land can be fertilized annually using faecal sludge generated in the Tamale municipality alone. For Bolgatanga, the potential area covered is much lower, about 52 ha, under the same application rates. Optimal FS application rates have not been determined for Northern Ghana. This requires further research, to provide guidance for farmers and municipal authorities.

Problems associated with the use of faecal sludge: farmers' perspectives

During focal group discussions and interviews with farmers, the following issues were highlighted as the main constraints associated with use of FS for crop cultivation (Fig. 6):

- Bad odor. About half of respondents (47%) indicated that bad odor of FS is a major constraint to its use. Farmers are not allowed to use sludge in backyard gardens, particularly in highly populated areas.
- Competition for FS. Twenty-four percent of surveyed farmers complained of competition for FS. Some farmers must wait for 1–2 months from the time of request until FS is delivered to their farms.
- Increase in urban population. As agricultural lands become human settlements, FS users are pushed towards

peri-urban areas. Moreover, suction truck drivers are reluctant to deliver faecal sludge to fields too distant from cities as it is not profitable. Fourteen percent of respondents indicated that transport is a problem.

- Negative attitude of other people towards the use of human waste. Landlords often do not allow use of FS on their land despite positive effects on soil fertility. This is probably due to concerns about weed build-up and odor.
- Weed infestation (2%). Due to its high fertilization effect, FS increases weed populations.
- Need for protective clothing and extra labor during FS application (4%).
- Death of the crop when FS is applied in excess (1%).
- Consumer shunning of crops produced using FS (4%). Some people believe that taste is diminished and there is a tendency for maize and millet to be reddish in color.
- Health problems associated with handling FS. Some 24% of farmers had experienced health problems during land preparation involving FS, which was done without protective foot covering. While 22% experienced itching feet and foot rot, 2% observed headache and catarrh. This observation was irrespective of the method of FS application. All farmers who had experienced itching feet were residents of three communities in Bolgatanga, while those complaining of foot rot belonged to three communities in Tamale. However, both groups comprised less than half of the surveyed farmers in either community. Itching feet and foot rot are probably due to excreted parasitic helminth worms capable of penetrating bare feet. This indicates that some microorganisms remain viable in spite of the long drying period.

Conclusions

For many years, farmers in the guinea savanna zone of Ghana have used FS in agriculture. Sludge discharged on farms during the dry season is incorporated into the soil at the start of the rainy season, after 3–4 months of drying. Constraints associated with this practice include competition for FS, foul smell of the sludge, lack of transport, excessive weed infestation and health issues, primarily itching feet and foot rot following FS application. Yet, these concerns do not hinder farmers from scouting for FS at the onset of the drying season. Farmers are motivated to use FS because it: (1) is an inexpensive alternative to fertilizer; (2) increases the productive capacity of the soil; (3) results in increased crop yields; and (4) improves household food security and earnings.

However, there is a need to educate farmers regarding modes of disease transmission and the proper handling of FS, using protective boots, nose pads and hand gloves. Information on simple cost-effective methods for decontaminating FS is also needed. Presently, farmers use an extended drying period to decontaminate FS, but the frequent occurrence of foot rot and other health problems suggests that some pathogens are not eradicated by this approach. In Ghana, further research is needed to assess: (1) the impact of FS use on agricultural productivity and crop quality, especially in comparison with manure and fertilizer; (2) optimal FS application rates; and (3) the long-term consequences of FS use on farmer/consumer health and the environment.

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Comparing agroecosystems: Effects of cropping and tillage patterns on soil, water, energy use and productivity

Megan M. Gregory, Kathleen L. Shea* and Eugene B. Bakko

Department of Biology, St. Olaf College, Northfield, MN 55057, USA.
*Corresponding author: sheak@stolaf.edu

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Abstract

We compared soil characteristics, runoff water quantity and nutrient fluxes, energy use and productivity of three farm types in an unusually dry farming season: conventional (continuous corn and deep tillage), rotation (5-year corn–soybean–oats/alfalfa–alfalfa–alfalfa rotation with tillage 2/5 years) and no-till (corn–soybean with no cultivation). Soil organic matter content was highest on the rotation farm, followed by the no-till farm, and lowest on the conventional farm. Nitrate content of the soil did not differ significantly among the three farms, although the conventional farm had a much higher input of fertilizer nitrogen. Soil penetrometer resistance was lower and percent soil moisture was higher in the no-till and rotation systems compared to the conventional farm. Soil macroinvertebrate abundance and diversity were highest on the no-till farm, followed by the rotation farm. No invertebrates were found in the soil of the conventional farm. The conventional farm had the highest runoff volume per cm rain and higher nitrogen (N) loss in runoff when compared to the rotation and no-till farms, as well as a higher phosphorus (P) flux in comparison to the no-till farm. These results indicate that perennial close-seeded crops (such as alfalfa) used in crop rotations, as well as plant residue left on the surface of no-till fields, can enhance soil organic content and decrease runoff. The lower soil penetrometer resistance and higher soil moisture on the rotation and no-till farms show that conservation tillage can increase soil aggregation and water infiltration, both of which prevent erosion. Furthermore, crop rotation, and particularly no-till, promote diverse invertebrate populations, which play an important role in maintaining nutrient cycling and soil structure. Crop rotation and no-till agriculture are less fossil-fuel intensive than conventional agriculture, due to decreased use of fertilizers, pesticides and fuel. In this unusually dry year they provided superior corn and soybean yields, most likely due to higher soil moisture as a result of greater water infiltration and retention associated with cover crops (rotation farm) and crop residue (no-till farm).

Key words: sustainable agriculture, crop rotation, no-till agriculture, soil organic matter, soil compaction, soil invertebrates, agricultural runoff, fossil fuel consumption, corn–soybean productivity

Introduction

In recent years there has been growing concern from farmers, scientists, economists, sociologists, and religious leaders regarding the sustainability of current agricultural practices in the United States[1–2]. Monoculture row cropping, deep tillage and application of high levels of fertilizers and pesticides can result in widespread damage to land and water resources. Conventional agriculture in the US also depends heavily on fossil fuel energy, thus contributing to rising CO_2 levels and global climate change. In order to address the problems of conventional agriculture, some farmers are seeking more sustainable methods of agriculture, including crop rotation, no-tillage and integrated pest management.

Legume-based crop rotations, no-tillage agriculture and reduction of pesticide application can have positive effects on soil, water, energy use and productivity in agroecosystems. While monoculture row cropping tends to deplete soil organic material and nitrogen, crop rotations (particularly those including perennial legumes) tend to restore these essential materials to the land[3–8]. Crop residue left on the surface of no-till fields provides organic matter that enhances soil aggregation and water-retaining capacities, both of which reduce runoff and pollution of aquatic systems[9]. Reduced tillage has also been shown to increase populations of soil macroinvertebrates, which contribute to decomposition and nutrient cycling, a porous soil structure and natural pest control[10–14]. With regards to economic

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Table 1. Cultural practices on the study farms.

Study farm	Cropping history					Tillage
	2003	2002	2001	2000	1999	
Conventional corn (CC)	C	C	C	C	C	Moldboard plow
Conventional soybeans (CS)	S	C	C	S	C	Chisel plow/disk ripper
Rotation corn (RC)	S	C	A	A	A	Mulch till (only before C and S)
Rotation soybeans (RS)	S	C	A	A	A	Mulch till (only before C and S)
Rotation alfalfa (RA)	A	A	S	C	A	Mulch till (only before C and S)
No-till corn (NTC)	C	S	C	S	C	No tillage
No-till soybeans (NTS)	S	C	S	C	S	No tillage

C, corn; S, soybeans; O, oats; A, alfalfa.

Table 2. Comparison of 2002, 2003 and 1971–2000 average precipitation levels by month, growing season totals (June–October) and year totals (January–December) at the Faribault, Minnesota weather station (#212721)[16,17].

	2002 Precipitation (cm)	2003 Precipitation (cm)	1971–2000 Average precipitation (cm)
January	1.63	0.89	2.67
February	1.40	2.01	1.83
March	5.82	4.50	4.90
April	8.38	5.56	7.14
May	4.70	12.04	9.50
June	26.09	10.77	10.64
July	10.77	6.15	10.90
August	14.55	4.19	11.28
September	7.42	3.96	8.13
October	10.19	2.01	5.66
November	0.33	2.95	5.13
December	1.30	2.97	2.59
Growing season (June–October)	69.01	27.08	46.61
Year total (January–December)	92.56	57.99	80.37

concerns, studies show that conservation practices such as no-till agriculture can increase productivity and decrease costs[15].

The purpose of our study was to evaluate the effects of crop management practices on soil quality and sustainability of agroecosystems in south-central Minnesota. This was accomplished by comparing soil characteristics, water quantity and nutrient fluxes in runoff, energy use and productivity in conventional, crop rotation and no-till farms. Since the 2003 growing season was unusually dry, this study also provides insight into the performance of these farming systems under extreme conditions.

Materials and Methods

In order to assess the effects of crop rotation and no-tillage agriculture, we sampled soil and macroinvertebrate populations from three farm types (conventional, rotation and no-till) with different cropping and tillage methods near Northfield, Minnesota, USA (Table 1). The farms sampled are within 3.5 km of each other, just north or west of the St. Olaf College campus. The farm soils are classified mainly as Lester loams with 2–6% slopes[16]. The conventional corn (CC) field was continuously cropped with corn and tilled with a moldboard plow. The conventional soybean (CS) field was in a corn–corn–soybean (C–C–S) rotation and cultivated with a chisel plow and disk ripper each year. Rotation fields were in a perennial-legume-based, 5-year crop rotation of corn–soybeans–oats/alfalfa–alfalfa–alfalfa (C–S–O/A–A–A). Fields were mulch-tilled before planting of corn and soybeans, but were not tilled during the 3 years that alfalfa was grown. Manure had been applied before planting of corn on the rotation farm over the past 10 years. The no-till farm used a corn–soybean (C–S) rotation and a seed drill to plant directly into the soil through the residue of the previous year's crop, which was left undisturbed following harvest. In 2003, this farm had been under no-till management for 12 years.

Precipitation levels before and during our study in the fall of 2003 were unusually low (Table 2). From January through December of 2003, the Faribault, Minnesota weather station (approximately 18 km south of Northfield)

received 57.99 cm of precipitation[17], as compared with a 1971–2000 average of 80.37 cm[17]. During the 2003 growing season (June through October), the Faribault weather station received only 27.08 cm of precipitation[17], as compared with a 1971–2000 average of 46.61 cm[18].

Soil resources

In order to assess soil organic matter, soil nitrates, compaction and moisture, soil samples were collected on 3 days from early September through early October, in 2002 and 2003. In 2002, soil samples were taken from conventional corn (CC), rotation corn (RC) and no-till corn (NTC) fields. In 2003, soil samples were taken from conventional corn (CC), conventional soybean (CS), rotation soybean (RS), rotation alfalfa (RA), no-till corn (NTC) and no-till soybean (NTS) fields. The data presented are from the more extensive 2003 study, with 2002 trends noted in the text.

At each visit to the study sites, we combined five soil cores, 25 cm deep and 2 cm in diameter, from randomly chosen areas for tests of soil organic matter and nitrates, for a total of six samples per farm type. We determined percent organic matter in the soil by finding the ash-free dry weight of a soil subsample, oxidized in a muffle furnace at 500°C for 2 h. Percentage soil organic matter (% SOM) by weight was determined using the formula:

$$\%\mathrm{SOM} = [(W_{ad} - W_{af})/W_{ad}] \times 100\%$$

where W_{ad} = air-dry weight of soil sample and W_{af} = ash-free weight of soil sample. Nitrate analysis was performed by spectrophotometry as described by Hach Company[19].

In order to compare the soil moisture, we took two randomly selected 25 cm deep soil cores on each visit for a total of 6 per field and 12 per farm type. Soil cores were placed in pre-weighed metal tins and re-weighed in the lab to determine fresh weight, then oven-dried at 105°C for 48 h and weighed again to obtain dry weight. Percent soil moisture by weight (θ_w) was calculated by:

$$\theta_w = [(W_f - W_{od})/W_{od}] \times 100$$

where W_f = fresh weight of soil sample and W_{od} = oven dry weight of soil sample.

Soil compaction was determined for each field in 2003 using a Dickey–John penetrometer. Sixteen randomly selected sites were measured in each farm type (eight sites per field). Soil compaction readings were taken at depths of 15 cm and 30 cm.

The exceptional dryness of the 2003 growing season (Table 2) precluded an accurate sampling of invertebrate populations in the top 20 cm of soil, so data from 2002 are presented. Data were collected from conventional corn (CC), rotation corn (RC) and no-till corn (NTC) fields. We examined two randomly chosen plots per farm on 3 days for a total of six samples per field. We used a 25 × 25 cm quadrat frame and excavated to a depth of 20 cm, then searched the soil by hand for macroinvertebrates and recorded the number and classification of each invertebrate in each plot[20]. Insects and other arthropods were classified to order and class, respectively, and earthworms were classified into epigeic, endogeic and anecic functional groups[21]. These functional groups actually reveal more about an organism's response to environmental change than taxonomic groups, as members of particular functional groups tend to dwell in the same soil layer and utilize similar food sources[22]. Data from all six quadrats on each farm were pooled and used to calculate the Simpson (D) and Shannon (H) diversity indexes, respectively, using the following formulas[23]:

$$D = 1 - \Sigma p_i^2$$

$$H = -\Sigma p_i (\ln\ p_i)$$

where p_i = proportion of individuals of a given species.

Water resources

In order to assess the effects of different farming practices on runoff water quantity, we installed a catch-basin in each field to capture runoff (Fig. 1). After two rainstorm events, we collected the water in the buckets of each catch-basin and measured the volume of water collected in a graduated cylinder. We then centrifuged the samples at 5000 rpm for 5 min to remove sediment, decanted the liquid into a separate container, and filtered the water samples through a glass fiber filter. Concentrations of inorganic nitrogen (N) and orthophosphates (P) were determined using the methods described by Sechtig[24] and Liao[25], respectively. N and P concentrations in runoff were converted to fluxes (mg N cm^{-1} rain and μg P cm^{-1} rain) by multiplying concentrations by the volume of runoff water obtained.

Energy use and productivity

In order to compare energy use on the farms, we collected data from each farmer on per-acre application of fertilizer, herbicide and insecticide, as well as fuel required to operate farm machinery for each crop grown. The Handbook of Energy Utilization in Agriculture[26] was used to find percent active ingredient in agricultural chemicals, and the reference Food and Energy Resources[27] was used to convert kilograms of agricultural chemicals and gallons of fuel used into kcal ha^{-1} yr^{-1}. For each farm type (conventional, rotation and no-till) we estimated average yearly fossil fuel energy use. Data on crop yields in bushels $acre^{-1}$ (or bales $acre^{-1}$) were collected from each farmer at the end of harvest season and converted to kg ha^{-1} (or bales ha^{-1}). Conversions of bushels ha^{-1} to kg ha^{-1} assumed standard bushel weights: corn, 56.00 lbs $bushel^{-1}$ (15.5% moisture); soybeans, 60.00 lbs $bushel^{-1}$ (13.00% moisture); oats, 32.00 lbs $bushel^{-1}$ (14.00% moisture).

Data analysis

We determined mean % SOM, soil nitrate concentration, soil compaction, soil bulk density, soil moisture, invertebrate abundance, water runoff cm^{-1} rain, and fluxes of

Figure 1. A catch-basin constructed to assess the effects of agriculture (rotation soybean field) on soil runoff. Catch-basins consisted of a bucket, 9 in. (23 cm) in diameter, placed into a hole dug in the ground, beneath a raised plywood shelter. The shelter ensured that no rainwater would enter the bucket directly, and therefore that all water collected represented surface runoff from the fields. Pieces of plywood, 4 ft (1.2 m) long, were placed to form a 90° angle with the bucket at its vertex. This standardized the width of the collecting area to approximately 5.7 ft (1.7 m).

N and P in runoff for the three categories of farms. Because our data sets did not exhibit equal variances, we compared means using the nonparametric Kruskal–Wallis test using StatView 5.0 software[28].

Two-sample *t*-tests were used to compare the Simpson and Shannon diversity indexes between fields[23]. It was not possible to calculate a diversity index for the conventional farm because no invertebrates were found there.

Results and Discussion

Soil resources

Soil organic matter (SOM) was highest on the rotation farm, followed by the no-till farm, with the lowest soil organic matter levels on the conventional farm ($P = 0.0034$; Fig. 2).

These findings are consistent with studies on nutrient cycling in agroecosystems demonstrating a loss of soil organic matter in conventionally cropped and tilled soils[4,9] and an increase in SOM in cropping systems incorporating perennial legumes[5]. On the farm practicing a 5-year crop rotation, the high SOM content may be attributed to decreased erosion due to the presence of soil-conserving alfalfa crops during 3 out of every 5 years, as well as plant residues left by perennial legumes[7,29]. Decreased erosion due to protection of soil surface by plant residues may have also contributed to the relatively high levels of SOM on the no-till farm. Slower processes of biological oxidation on the no-till farm[4,8,11] and stimulation of fungal growth, which have a high efficiency of carbon assimilation[9] may

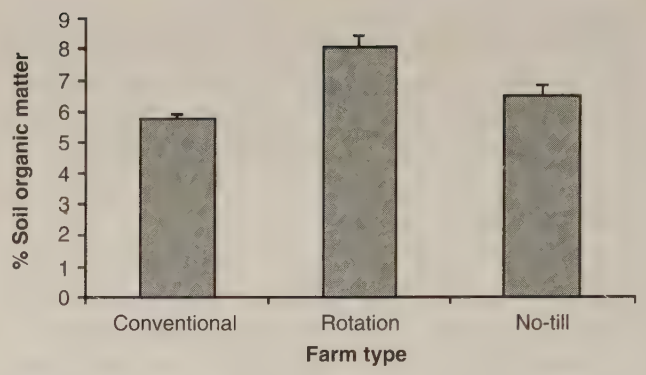

Figure 2. Percent soil organic matter by weight in conventional, rotation and no-till agroecosystems. Organic matter was calculated from soil cores 25 cm deep. Means ± standard error are shown. ($N = 6$, $P = 0.0034$).

also help account for the higher levels of SOM on the no-till farm compared to the conventional farm.

Our 2003 data, showing the highest SOM levels on the rotation farm, followed by the no-till farm, with the lowest SOM levels on the conventional farm, corroborated our initial findings from 2002. In 2002, we found soil organic matter levels of $3.97 \pm 0.05\%$ on the conventional farm, $7.81 \pm 0.75\%$ on the rotation farm, and $5.86 \pm 0.17\%$ on the no-till farm ($P = 0.003$). Organic matter levels on each farm remained fairly consistent from 2002 to 2003. The apparent increase in SOM for the conventional farm from 2002 to 2003 may be due to the fact that in 2002, we sampled only fields tilled with a moldboard plow (the most intensive form of tillage), while in 2003 we included fields tilled with a disk ripper (a less intensive form of tillage) in the conventional category.

It should be noted that if soil organic matter was calculated on a volume basis rather than a weight basis, the differences between the conventional farm and the rotation and no-till farms might be somewhat reduced, owing to the greater compaction, and therefore greater bulk density, of soil on the conventional farm (see below). However, the relatively higher percent soil organic matter by volume on the conventional farm in 2003 may not necessarily have a positive impact on crop growth, as it has been shown that root growth decreases as compaction (penetration resistance) increases[30]. With a smaller root surface area in contact with the soil, crops grown in compacted soil may be less able to take up nutrients released as organic matter decomposes.

Soil nitrates did not show significant differences between farms in 2002 ($P = 0.243$) or 2003 ($P = 0.8539$). However, other experiments have indicated the beneficial effects of perennial legumes and no-till agriculture on soil nitrogen. Because legume crops possess symbiotic (mutualistic) nitrogen-fixing bacteria in their root nodules, crop rotation incorporating perennial legumes has been shown to contribute to higher soil nitrogen levels[5,7,11,29]. No-till farms are also likely to retain more soil nitrogen than conventionally tilled farms, due to decreased erosion and loss of small organic particles to which nitrogen is bound[4,31].

There are several possible reasons why we did not observe higher nitrogen levels on the rotation and no-till farms in comparison to the conventional farm. First, nitrate levels were highly variable. The small sample size used may not have been representative of the actual levels of soil nitrogen or large enough to resolve differences between farms. The second possible explanation lies in the nitrogen fraction tested. We only tested soil for nitrate, an inorganic ion (NO_3^-). However, much of the nitrogen in the legumes of the rotation and no-till farms (soybeans and alfalfa) is contained in ammonia or organic forms. Total soil nitrogen levels may have been much higher than the nitrate levels indicate on the rotation farm in particular (with soybeans + 3 years of alfalfa), but also on the no-till farm (with soybeans every other year). Indeed, a study by Drinkwater et al.[5], which showed increased nitrogen levels in crop rotations with perennial legumes, considered nitrogen stored in above- and below-ground biomass (litter and roots).

Higher nitrogen fertilizer application on the conventional farm may also account for the fact that soil nitrogen levels were not significantly lower than the rotation and no-till farms. (Average N applications for each farm in 2003, including NH_3-N and NPK-N, were: 187.3 kg ha^{-1} on the conventional C–C–C farm, 124.9 kg ha^{-1} on the conventional C–C–S farm, 49.2 kg ha^{-1} on the rotation farm, and 67.5 kg ha^{-1} on the no-till farm.) However, studies have shown that inorganic nitrogen fertilizers cannot substitute for biologically fixed nitrogen added directly to the soil via legumes. Inorganic nitrogen is likely to be leached during the fallow period, or lost to soil erosion or denitrification, rather than retained in the soil[5,29]. Thus, high levels of soil nitrogen observed on the conventional farm may not persist.

Soil compaction at both 15 and 30 cm depths (Fig. 3) was lowest on the no-till farm, followed by the rotation farm. The conventional farm had the most compacted soil. Lower levels of soil disturbance, less use of heavy machinery[32], and higher levels of organic matter[7,33] may have promoted greater soil aggregation on the no-till and rotation farms compared to the conventional farm. Since aggregates help maintain pores of various sizes, one would expect the organic-matter-rich soil from these farms to be more porous and less compacted than soil from the deep-tillage conventional farm[34].

Evidence regarding the effects of decreased tillage on soil structure is somewhat contradictory. While some studies have observed an increase in bulk density in fields converted to no-till (the opposite of the trend toward decreased compaction that we observed), our findings are consistent with other studies that found a decrease in bulk density of no-till fields, particularly when organic matter content of the soil increased[30,33]. The no-till fields in our study may have exhibited less soil compaction than the conventional fields because the no-till fields we sampled have been under no-till management for more than 10 years. In contrast, a study showing greater bulk density in no-till fields[30] sampled from fields converted from conventional tillage to no-till within the past 5 years. There is often a temporary increase in soil bulk density and compaction following conversion from conventional tillage to no-till, until the soil recovers its natural structure and builds up organic matter, which increases soil porosity and decreases bulk density and compaction[30,33]. Therefore, our findings of decreased compaction in fields under no-till management for more than 10 years may not be in conflict with studies showing greater soil bulk density in no-till fields, if these studies were conducted early in the field's conversion to no-till.

Soil moisture levels were significantly higher in the rotation and no-till farms in comparison with the conventional farm (Fig. 4). These findings are consistent with a study by Holland and Coleman[9], which showed that leaving crop residue on the soil surface significantly decreased evaporation rates and resulted in moister soils than those of farms in which crop residue had been plowed under. Crop rotation and no-till agriculture may also increase soil moisture by increasing soil porosity and infiltration[1], while erosion due to conventional tillage practices can decrease infiltration by up to 93%[14]. In addition, no-till and reduced-till farming methods, such as those practiced on the rotation fields, may also have contributed to enhanced soil structure

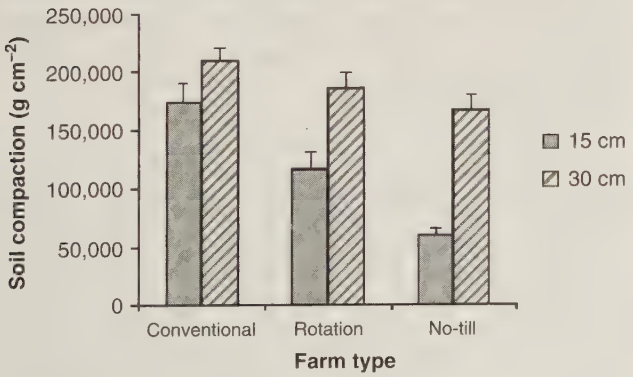

Figure 3. Soil compaction at 15 cm ($N = 16$, $P < 0.0001$) and 30 cm ($N = 16$, $P = 0.0520$).

Figure 4. Percent soil moisture by weight in conventional, rotation and no-till agroecosystems. Percent soil moisture was calculated from soil cores 25 cm deep. Means ± standard error are shown. ($N = 12$, $P = 0.0002$).

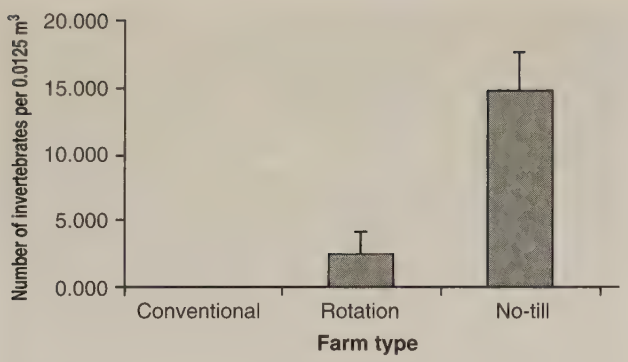

Figure 5. Soil invertebrate abundance in conventional, rotation and no-till agroecosystems. Invertebrate abundance is reported as average number of invertebrates found in a soil sample with a volume of 0.0125 m^3 (25 cm long × 25 cm wide × 20 cm deep). Means ± standard error are shown ($N = 6$, $P = 0.002$).

by supporting a greater abundance and diversity of soil invertebrates. This hypothesis is supported by our data on macroinvertebrates in the three farm fields (see below). Macroinvertebrate activities, such as burrowing, enhance formation of stable aggregates and increase porosity and water infiltration.

Although all the farm fields had lower moisture levels in 2003 than in 2002, due to the 2003 drought, we found similar trends in soil moisture in our 2002 study. The rotation farm had the highest soil moisture content, with 32.9 ± 3.2%, followed by the no-till farm with 24.0 ± 0.3%, and the conventional farm had the lowest soil moisture with 19.7 ± 1.2% ($P < 0.001$).

Soil invertebrates were most abundant on the no-till farm, followed by the rotation farm. No soil invertebrates were found in the soil of the conventional farm (Fig. 5). With regards to diversity, three functional groups of earthworms, five orders of insects, and three classes of other arthropods were found in the soil of the no-till farm. The three functional groups of earthworms were also observed on the rotation farm, but we found only one insect order (Coleoptera) and one other class of arthropods (Diplopoda). The Simpson (D) and Shannon (H) diversity indexes were higher for the no-till farm (D = 1.33; H = 2.04) than the rotation farm (D = 0.45; H = 0.83), and lowest (D = 0.00; H = 0.00) for the conventional farm. Our results are consistent with other studies documenting the greater invertebrate abundance and diversity in no-till farms when compared with conventional farms[10,14,20,33,35].

Soil disturbance, soil compaction and alteration of habitat due to use of the moldboard plow have been shown to decrease the biomass and diversity of soil invertebrate populations[10–14,20,33,35–41]. These factors could all play a role in the absence of invertebrate populations on the conventional farm, as the invertebrate-rich decomposition biotrope, dependent on the presence of plant litter on soil, is nearly eliminated in conventionally tilled fields[33]. Furthermore, tillage destroys the stratified surface soil horizons that provide a diversity of habitat niches in undisturbed soils. Excessive use of crop protection chemicals may also prove toxic to invertebrate populations, thus decreasing abundance and diversity[11,12,14,20]. Application of chemical pesticides, which was highest on the conventional farm, could have played a role in the lack of macroinvertebrates observed. These findings are supported by a previous study on St. Olaf farmland[42].

In contrast to conventional systems, no-till or minimum-till systems increase earthworm abundance, because the crop residue left on the soil surface promotes fungi-based food webs[36,40], protects earthworms from desiccation and predation[33] and provides a more stable microclimate at the soil surface[3,33]. Inclusion of legumes or fibrous root crops in rotation may also stimulate larger populations of soil invertebrates by increasing below-ground carbon and nitrogen inputs to the soil[10]. In our study, tillage practices appear to account for the differences in invertebrate abundance and diversity, as the no-till farm had the highest and most diverse invertebrate populations. Thus, monocrop farming and deep tillage (as on the conventional farm sampled) decrease the diversity of food sources and invertebrate habitats present in a natural system, resulting in less invertebrate abundance and diversity, while crop rotations and no-tillage agriculture preserve habitat and invertebrate diversity[13,41].

Water resources

Runoff volume per cm rain was highest on the conventional fields, averaging 35 times that of the no-till fields and 60 times that of the rotation fields (Table 3). Our results, indicating higher runoff in exclusively row-cropped, conventionally tilled agricultural fields, are consistent with those of other investigators. Other studies have shown that no-till systems[33] and less intensive tillage[43] systems also reduce runoff volume.

Table 3. Water resources data for conventional, rotation and no-till agroecosystems found in 0.0125 m^3 soil samples. Means ± standard error are shown.

	Sample no. per farm	Conventional	Rotation	No-till	*P* value
Runoff volume (ml cm^{-1} rain)	4	684.6 ± 631.3	11.7 ± 9.6	19.5 ± 11.6	0.0244
N flux in runoff (mg N cm^{-1} rain)	4	0.3 ± 0.3	0.0 ± 0.0	0.0 ± 0.0	0.2621
P flux in runoff (μg P cm^{-1} rain)	4	14.0 ± 12.0	44.2 ± 37.8	2.9 ± 2.1	0.7718

Several factors may have contributed to reduced water losses from the rotation and no-till systems in our study. As discussed previously, increased ground cover and root area (from perennials on the rotation farm and crop residues left on the surface of no-till fields) increase infiltration of rainwater, thus decreasing runoff[3,33]. More porous, less compacted soil structures on the rotation and no-till farms may also play a role in reducing runoff volume.

The conventional farm also had higher N loss in runoff when compared to the rotation and no-till farms, as well as a higher P flux in comparison to the no-till farm (Table 3). Although these differences were not statistically significant, this is probably due to the very limited sample size (two samples per field), owing to lack of rainstorm events during the study. The lower N fluxes in runoff from rotation and no-till farms, and lower P fluxes from the no-till farm, in comparison to the conventional farm, are consistent with other studies on transport of nutrients in agricultural systems. For example, elevated NO_3^- concentrations have been observed in runoff from corn monocultures[44]. Other studies have also shown that no-tillage agriculture can reduce sediment and associated phosphorus losses to aquatic systems[43,45,46].

Our observation that the conventional farm exhibited higher N fluxes in runoff than the rotation and no-till farms was probably due to high fertilizer use combined with high leaching due to shallow rooting systems on the conventional farm. In comparison to biologically fixed nitrogen, plants tend to use such fertilizer nitrogen inefficiently, leaving excess nitrate ions to be leached into the watershed as nutrient pollution[29,47]. On the other hand, rotation of corn with soybeans and alfalfa decreases the amount of fertilizer that must be applied to obtain good yields. Lower fertilizer use may explain the lower N fluxes observed in runoff from the rotation fields, as no fertilizer was applied during the years in which soybeans and alfalfa were grown (4 out of every 5 years).

Lower nutrient fluxes of N and P in runoff from the no-till fields in comparison to the conventional fields may be attributed to the fact that no-till farming prevents erosion by providing physical protection from wind and rain, and by increasing water infiltration rates (as discussed previously). Given that about 75–90% of P exported from cultivated lands is adsorbed to soil particles eroded in runoff, decreased erosion on the no-till farm due to plant residues on the soil surface could substantially reduce P loss[48].

The elevated P loss from the rotation agroecosystem as compared to the conventional system is somewhat perplexing. The high P loss from the rotation system is entirely attributable to P loss from the alfalfa fields, as the rotation soybean fields had no runoff during either rainstorm event. Given the high proportion of ground cover and therefore the presumably low soil erosion rates in the alfalfa fields, one would expect lower loss of P in surface runoff. The high levels of P in runoff from the rotation alfalfa fields may be the result of manure application or P accumulation in crop residues near the soil surface, where it can be transported to runoff[45]. Further research is needed to determine if P loss is actually higher on the alfalfa fields in comparison to other fields, and to elucidate the mechanism for P loss in such a low-erosion, cover-crop environment.

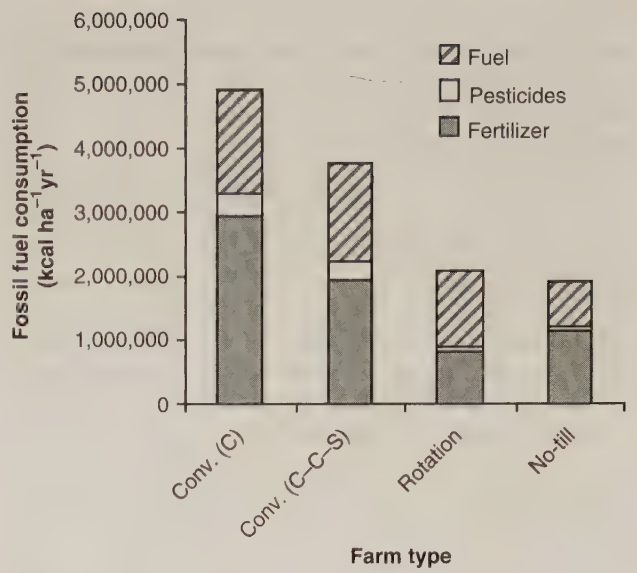

Figure 6. Fossil fuel energy consumption (kcal ha^{-1} yr^{-1}) in conventional (C–C–S), rotation (C–S–O/A–A–A) and no-till (C–S) agroecosystems during the 2003 growing season.

Energy use and productivity

Fossil fuel consumption was highest on the conventional farms, followed by the rotation and no-till farms (Fig. 6). The conventional farm had the highest energy consumption for fertilizer, pesticides and fuel when compared with the rotation and no-till farms.

On the rotation and no-till farms, crop rotation and decreased rates of soil erosion may have reduced the need for fertilizer and pesticide consumption, thus decreasing energy use. Perennial legumes such as alfalfa are capable of contributing over 200 kg of N ha^{-1} to the soil, which is sufficient to meet the nitrogen requirements of most subsequent grain and cover crops[3,49]. The low erosion rates associated with crop rotation and no-tillage agriculture can also greatly reduce nutrient losses from these systems, obviating the need for high inputs of inorganic nutrient application. Crop rotation also enhances pest control by breaking pest life cycles, thus decreasing the amount of chemical pesticides that must be applied. For example, rotating corn and soybeans eliminates the need for insecticides to control rootworm pests[50]. This can be seen in that the most diversified farm—the rotation C–S–O/A–A–A—had the lowest energy consumption due to pesticide use.

No-till agriculture greatly reduced the energy consumption associated with machinery and fuel use by eliminating plowing: the average total fuel use of no-till agriculture was less than half that of conventional agriculture. A study by West and Marland[51], which calculated C emissions due to

machinery energy consumption (averaged over corn, soybean and wheat), found even greater differences between conventional and no-till fields. While conventional tillage resulted in emissions of 69.0 kg C ha^{-1} yr^{-1}, no-till fields were responsible for 23.3 kg C ha^{-1} yr^{-1}.

Although not as low as fuel use on the no-till farm, the rotation farm also had lower fuel use than the conventional farm, mainly due to reduction in the intensity and frequency of plowing (fields are tilled only before planting of corn and soybeans and are left unplowed during the 3 years that alfalfa is grown). However, the rotation farm used fuel for cutting, raking and baling of alfalfa that was not needed in either the conventional or the no-till system.

Our calculations indicate that rotation and no-till systems use substantially less fossil fuel in comparison to conventional systems. This alone indicates that crop rotation and no-till agriculture could play an important role in mitigating global climate change, were they adopted on a large scale. However, the benefits of crop rotation and no-till in reducing radiative forcing of the atmosphere include not only decreased fossil fuel emissions, but also increased carbon storage in soil organic matter. A study of the global warming potential (GWP) of different agricultural systems[52] found that carbon accumulated at a rate of 44.0 g C m^{-2} yr^{-1} in a perennial alfalfa field and 30.0 g C m^{-2} yr^{-1} in a no-till field, while a conventionally tilled field accumulated no carbon. The net GWP for the alfalfa field was actually negative (−20 g CO_2 equivalents m^{-2} yr^{-1}), and that of the no-till field was less than one-eighth that of the conventional field (14 compared to 114 g CO_2 equivalents m^{-2} yr^{-1}).

Per-hectare production of corn and soybean crops was greater on the rotation and no-till farms than on the conventional farms (Table 4). This concurs with a 1996 study comparing the conventional and rotation farms. Although the no-till system was not included in this study, per-hectare production of corn and soybean crops was greater on the rotation farm than on the conventional farm[42].

A number of factors associated with soil fertility may have contributed to increased yields on the rotation and no-till farms in our study. First, the higher levels of organic matter on the rotation and no-till farms may have increased their yields relative to the conventional farm. The majority of available nutrients needed for crop growth are contained in organic matter: 95% of available nitrogen and 25–50% of available phosphorous in the soil are contained in organic matter[11,14]. Improved soil structure and decreased erosion rates may also have contributed to superior yields on the rotation and no-till farms. Topsoil losses associated with monoculture row cropping and deep tillage (as on the conventional farm) can significantly decrease soil fertility, water infiltration and holding capacity, and beneficial soil biota, thus reducing crop yields[14]. Due to the lack of growing season precipitation in the 2003 growing season, increased water infiltration and retention associated with cover crops (on the rotation farm) and crop residue (on the no-till farm) could have been a major factor in increasing the yields of the rotation and no-till farms in comparison to the conventional farm. Finally, increased invertebrate activity on the rotation and no-till fields could have increased soil fertility and soil moisture, and therefore productivity. This hypothesis is supported by an experiment comparing farm fields before and after the introduction of earthworms, which found a 28% increase in production and a 100% increase in water infiltration 10 years after introduction[53]. Crop diversity on the rotation farm may also have increased productivity by preventing crop losses due to pest and disease outbreaks[54].

Summary and Conclusions

Design of sustainable agroecosystems necessitates that we understand the effects of farming practices on the long-term sustainability of soil and water resources. Nutrient content, resistance to erosion and soil invertebrates are all important aspects of an agroecosystem that must be considered in plans for maintaining the fertility and productivity of the soil. This study indicated that crop rotation and reduced tillage have a number of positive effects on the ecological sustainability of agroecosystems.

Soil organic matter was highest on the rotation farm, followed by the no-till farm, and lowest on the conventional farm. The crop diversity and plant residue left on the soils of these fields, as well as the continuous ground cover provided by alfalfa in the rotation fields, prevented erosion and increased soil organic content, which is critical for crop growth. Our study also indicated that no-tillage and minimum-till agriculture have positive effects on soil structure. Soil compaction was lower and percent soil moisture was higher in the no-till and rotation fields compared to the conventional fields. Less use of soil-compacting heavy machinery and greater retention of organic matter in these soils promoted aggregate formation, maintained porosity and increased water infiltration, all of which served to enhance the physical structure of the soil and decrease

Table 4. Productivity of conventional, rotation and no-till agroecosystems for the 2003 growing season.

Crop	Conv. (C)	Conv. (C–S)	Rotation (C–S–O/A–A–A)	No-till (C–S)
Corn: kg ha^{-1} (bushel $acre^{-1}$)	7407 (118)	7407 (118)	9416 (150)	8286 (132)
Soybeans: kg ha^{-1} (bushel $acre^{-1}$)	–	1345 (20)	2556 (38)	2421 (36)
Oats, seeds: kg ha^{-1} (bushel $acre^{-1}$)	–	–	3228 (90)	–
Oats, straw: bales ha^{-1} (bales $acre^{-1}$)	–	–	148 (60)	–
Alfalfa: bales ha^{-1} (bales $acre^{-1}$)	–	–	370 (150)	–

susceptibility to erosion. No-till and minimum-till methods of cultivation were also less disruptive of soil invertebrates, which helped maintain fertility and physical structure of the soil. Indeed, we found that invertebrate diversity and abundance was highest on the no-till farm and lower on the reduced-tillage rotation farm, while the soil tilled with a moldboard plow on the conventional farm supported no invertebrates.

Water quality is another concern that must be taken into account in order to reduce the environmental impacts of agriculture, which often contributes to eutrophication and pollution of aquatic ecosystems. We found that the rotation farm had the lowest runoff levels, followed by the no-till farm. The conventional farm had the highest volume of runoff and the highest N loss in runoff. Lower fertilizer application and increased ground cover due to perennial crops and crop residues on the rotation and no-till fields may have played a role in increasing infiltration of rainwater, thus decreasing runoff.

In light of decreasing fossil fuel energy supplies and the threat of climate change due to increased CO_2 inputs to the atmosphere, reducing fossil fuel use in agriculture should also be a priority. Our study indicated that the crop rotation and no-till farms consumed much less fossil fuel than the conventional farms, due to lower inputs of fertilizers, pesticides and fuel.

Finally, productivity must also be considered when comparing agricultural systems, as a farm must be economically, as well as ecologically, sustainable. Our study and other research demonstrating the positive effects of perennial legume-based crop rotations and no-tillage agriculture on agroecosystem productivity[3–8] indicated that adoption of practices such as those on the rotation and no-till farms sampled could have both environmental and economic benefits. Such research must be integrated with the political, social and philosophical aspects of agricultural activity in order to ensure sustainability of human food resources and rural communities.

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Agronomic performance of Pesticide Free Production under two crop rotations

A. Schoofs[1], M.H. Entz[1,*], R.C. Van Acker[1], J.R. Thiessen Martens[1] and D.A. Derksen[2]

[1]Plant Science Department, University of Manitoba, Winnipeg, MB, R3T 2N2, Canada.
[2]Brandon Research Centre, Agriculture and Agri-Food Canada, Brandon, MB, R7A 5Y3, Canada.
*Corresponding author: m_entz@umanitoba.ca

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Abstract

Pesticide Free Production (PFP) is a pesticide reduction system that removes in-crop pesticide use on a yearly basis. A long-term study was established in 2000 to investigate the effect of crop rotation and frequency of inclusion on the success of PFP, as well as the effect of PFP on subsequent crops in the rotation. The crop rotations being compared were linola–oat–canola–wheat and linola–oat–alfalfa–alfalfa. PFP occurred either once in the rotation (oat) or twice (linola–oat). Weed density and yield were measured in the crops that followed PFP. Oat was a more successful PFP crop than linola because it was better able to compete with weeds. Furthermore, PFP oat had a higher weed density when it followed PFP linola, but this did not influence PFP oat yield. Under the conditions of this study, PFP linola was more successful in the annual crop rotation. Inclusion of alfalfa hay crops in the crop rotation was not effective in lowering weed pressure and, in fact, may have contributed to an increase in weed density. It is concluded that weed species present influenced the effectiveness of alfalfa in facilitating PFP, because major weeds in the study are not effectively controlled by alfalfa. PFP did not have a negative effect on following crops in the rotation (i.e. canola–wheat or alfalfa), regardless of whether one or two consecutive years of PFP occurred in the rotation. No additional herbicide was necessary for weed control in the crops that followed PFP; however, alfalfa hay was weedier for the first year following PFP. This study indicates that PFP is a viable way to reduce herbicide use in a cropping system and that attention needs to be paid to PFP crop selection and crop rotation, particularly when the PFP crop is less competitive with weeds.

Key words: pesticide use reduction, crop rotation, alfalfa, intercropping

Introduction

The global food industry has recognized the limitations of current farming systems and is making changes to enhance sustainable agriculture. For example, several multinational food companies, such as Nestlé and Unilever, have joined the Sustainable Agriculture Initiative (SAI) Platform[1]. The SAI Platform aims for implementation of sustainable practices for mainstream agriculture (not niche markets) on a worldwide scale. The majority of farmers on the North American Northern Great Plains (NGP) will need to reduce their dependence on synthetic chemicals in order to fit into this evolving world market. Studies suggest, however, that farmers will not replace herbicide use with non-chemical weed management practices unless it is relatively easy to do so[2–4]. Based on this information, a production system called Pesticide Free Production (PFP) was developed by Canadian farmers and researchers as a practical means of reducing pesticide use in certain years. PFP is designed to appeal to many types of farmers. The primary goal of the PFP system is to reduce pesticide use on a large number of farms without sacrificing crop yield.

PFP is a production system in which non-genetically modified crops are grown without the use of pesticide, including chemical seed treatments, from the time of crop emergence until the time of marketing[5]. Residual activity of pesticides used prior to the PFP crop must have ceased, but use of non-residual pre-emergent pesticides, such as glyphosate [*N*-(phosphonomethyl)-glycine], is permissible. In addition to this, there are no restrictions on the use of fertilizer. PFP is compatible with no-till farming methods[6], which is of significance as no-till is currently practiced on 31% of the arable land in the Canadian prairie provinces[7]. On the Canadian prairies, a farmer may grow a crop following the PFP guidelines and have that crop certified as PFP for marketing purposes.

A participatory, on-farm study was conducted by Nazarko et al.[8] to assess the potential of PFP to be widely implemented on mainstream farms in Manitoba, Canada. Over 90% of farmers who achieved PFP certification in this

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study said that production of a PFP crop was at least as profitable as producing the same crop in a conventional manner. Furthermore, these farmers said that they did not expect to increase their future pesticide use due to incorporation of PFP within their crop rotation, thereby fulfilling the overall goal of pesticide reduction[6]. The findings of this study concluded that there is significant potential for the adoption of PFP in the Canadian prairie region of the NGP[8].

In the NGP, weeds are a major pest and are potentially the greatest limiting factor to adoption of PFP or similar pesticide reduction strategies. A review of the literature indicates that weed populations increase and yield decreases when herbicides are removed without the incorporation of integrated weed management techniques into the system. In a study by Légère et al.[9], chisel-plowed plots receiving no post-emergent herbicide had greater weed densities and lower barley (*Hordeum vulgare* L.) yield than plots that had received post-emergent herbicide. However, Derksen et al.[10] found that weed populations in low-input systems were similar to those of high-input systems when seeding date of the crop was delayed. Stevenson et al.[11] concluded that when cultural weed control measures (increased seeding rate, pre-seeding tillage close to time of seeding, and banding of N fertilizer) were implemented, no short-term yield loss was incurred in wheat (*Triticum aestivum* L.) and barley, when post-emergent herbicide was periodically reduced or eliminated from the system.

In the PFP on-farm study[8], farmers that chose historically weed-free fields for PFP, or were actively preparing for lower inputs, were more likely to be successful with PFP than those who chose fields based only on how clean they looked in the spring. The beneficial effects of crop rotation on weed populations and crop yields are well documented in the scientific literature[12–15]. In the study by Nazarko et al.[6], one of the most commonly cited strategies to prepare for PFP was crop rotation with forages. When surveyed, farmers in Manitoba and Saskatchewan said that they recognized that forages contributed to improved crop yields and reduced weed populations[16]. A survey of commercial grain fields by Ominski et al.[17] showed that inclusion of alfalfa (*Medicago sativa* L.) in a crop rotation can effectively suppress some weed species.

Results of the Nazarko studies[6,8] show that PFP can be practical at the farm level; however, there is still a need to validate the effects of PFP in the crop rotation over the long term. For example, will herbicide use reduction in the PFP years increase weeds and decrease yield of the following crops?

This paper presents the first 5 years of data of a field study on Pesticide Free Production. Because herbicides comprise over 85% of the pesticide used on the Canadian prairies[10], this study focuses on herbicide reduction. The objectives of this study were to: (1) determine the effect of PFP on weed population dynamics within the PFP and post-PFP crops in a 4-year rotation; and (2) determine the effect of PFP on yield of the PFP and post-PFP crops with the rotation. We hypothesized that: (1) inclusion of PFP in a 4-year crop rotation will increase weed populations within the PFP and post-PFP crops; (2) there would be no negative effect of PFP on yield of the PFP and post-PFP crops; and (3) weed populations in the PFP crops would be less and yield greater when 2 years of alfalfa is included in the rotation as opposed to canola followed by wheat. The objectives of this experiment were accomplished by measuring weed seedling density within the crop canopy, crop and weed dry matter at harvest and crop yield.

Materials and Methods

Field operations

This study was conducted from 2000 to 2004 at the University of Manitoba Field Station in Carman, Manitoba on an Orthic Black Hochfeld fine sandy loam soil. The study was fully phased, meaning that each crop in the rotation was present in every year of the study. The experimental design was a randomized complete block replicated three times. Plots were 4 m by 12 m in size and row spacing was 15 cm. There were six treatments comparing crop rotation and frequency of PFP in the crop rotation (Table 1). Oat and linola were the PFP crops in the rotation, whereas, canola, wheat or alfalfa were considered to be the post-PFP crops. In 2000, canola was grown in the place of linola (*Linum usitatissimum* L.), and it was not treated as PFP. The first occurrence of PFP linola was in 2001. The plots were all treated with no-till management. Row spacing, seeding rates, harvest and straw management used in this study were typical of no-till producers in western Canada. All plots were sprayed with $3.0\,l\,ha^{-1}$ glyphosate ($360\,g\,l^{-1}$ formulation) prior to, or just after, seeding each year. According to the PFP guidelines, a non-residual herbicide may be used prior to crop emergence.

All crops were no-till seeded into the stubble of the previous crop using a no-till offset disc press drill (Swift Machinery Co., Swift Current, Saskatchewan) (Table 2). Oat (*Avena sativa*, L., cv. AC Assiniboia) and wheat (cv. AC Barrie) were seeded at $130\,kg\,ha^{-1}$, canola (cv. Invigor 2663) was seeded at $8\,kg\,ha^{-1}$, alfalfa (cv. OAC Minto) was seeded at $12\,kg\,ha^{-1}$ and linola (cv. 1084 UGG) was seeded at $45\,kg\,ha^{-1}$. Seeding rates were chosen based on recommendations by Manitoba Agriculture, Food and

Table 1. Summary of treatments in the Pesticide Free Production (PFP) rotation trial at Carman, Manitoba.

Description	Rotation
Annual, 2 PFP crops	PFP linola–PFP oat–canola–wheat
Annual, 1 PFP crop	Linola–PFP oat–canola–wheat
Annual, control	Linola–oat–canola–wheat
Forage, 2 PFP crops	PFP linola–PFP oat–alfalfa–alfalfa
Forage, 1 PFP crop	Linola–PFP oat–alfalfa–alfalfa
Forage, control	Linola–oat–alfalfa–alfalfa

Table 2. Summary of seeding and harvest dates, and fertilizer additions for all rotational crops at Carman between 2000 and 2004.

				Nutrients (kg ha^{-1})			
Crop	**Year**	**Date seeded**	**Date harvested[1]**	**N**	**P_2O_5**	**K**	**S**
Linola (annual rotation)	2001	28 May	31 Aug./10 Sept.	96	34	0	24
	2002	15 May	4 Sept./12 Sept.	50	45	0	40
	2003	13 May	21 Aug./3 Sept.	72	48	34	34
	2004	18 May	17 Sept./27 Sept.	67	57	24	40
Linola (forage rotation)	2001	28 May	31 Aug./10 Sept.	96	34	0	24
	2002	15 May	4 Sept./12 Sept.	50	45	0	40
	2003	13 May	21 Aug./3 Sept.	38	48	51	34
	2004	18 May	17 Sept./27 Sept.	0	57	47	40
Oat (annual rotation)	2000	26 May	11 Sept.	0	52	0	0
	2001	14 May	17 Aug./20 Aug.	51	24	0	24
	2002	15 May	19 Aug./26 Aug.	50	45	0	20
	2003	5 May	13 Aug./22 Aug.	34	43	34	0
	2004	10 May	30 Aug./18 Sept.	50	27	0	0
Oat (forage rotation)	2000	26 May	11 Sept.	0	52	0	0
	2001	14 May	17 Aug./20 Aug.	51	24	0	24
	2002	15 May	19 Aug./26 Aug.	50	45	0	20
	2003	5 May	13 Aug./22 Aug.	34	43	56	0
	2004	10 May	30 Aug./18 Sept.	30	43	60	0
Alfalfa (Year 1)	2000	26 May	25 July/25 Sept.	0	52	0	0
	2001	14 May	13 July/23 Aug./17 Sept.	0	60	0	11
	2002	15 May	15 July/28 Aug.	0	45	0	20
	2003	6 May	22 July	0	48	22	0
	2004	10 May	4 Aug.	0	58	53	0
Alfalfa (Year 2)	2000	26 May	25 July/25 Sept.	0	52	0	0
	2001	–	20 June/30 July/13 Sept.	0	45	0	11
	2002	–	2 July/23 Aug.	0	52	0	20
	2003	–	23 June/8 Aug.	0	45	56	0
	2004	–	30 June/16 Aug.	0	45	77	0
Canola	2000	30 June[2]	3 Oct.	0	52	0	0
	2001	14 May	27 Aug.	96	34	0	24
	2002	15 May	12 Aug./26 Aug.	100	45	0	40
	2003	13 May	13 Aug./2 Sept.	150	48	34	34
	2004	18 May	30 Aug./18 Sept.	122	57	28	40
Wheat	2000	26 May	11 Sept.	0	52	0	0
	2001	14 May	17 Aug./20 Aug.	51	24	0	24
	2002	15 May	26 Aug.	100	45	0	20
	2003	5 May	22 Aug.	97	34	28	0
	2004	7 May	30 Aug./18 Sept.	50	34	0	0

[1] For grain crops, the first date refers to date swathed, the second date refers to date threshed; a single date indicates that the crop was straight combined.
[2] Reseeding date.

Rural Initiatives[18]. A range of seeding rates was recommended, and the upper end of the range was chosen for maximum competitiveness with weeds. It was decided that, to avoid confounding effects of nitrogen provided by the alfalfa in the forage-containing rotation, each crop would be fertilized with the amount of fertilizer necessary to meet specific crop demand, according to soil test recommendations made by an independent lab (Table 2). For example, in 2004, oat and linola following alfalfa required less nitrogen. Phosphate fertilizer (11–51–0) was applied with the seed. Potassium (0–0–62) was broadcast on all plots in 2003. Nitrogen (34–0–0) and sulfur (16–20–0–14), when required to meet crop demand, were banded to a depth of 8 cm immediately before seeding using the no-till press drill.

Broadleaved and grassy weeds were controlled in non-PFP plots using post-emergent herbicide at rates recommended by Manitoba Agriculture, Food and Rural Initiatives[19] (Table 3). Herbicides were chosen so that commercial activity would have ceased prior to PFP crop

Table 3. Summary of post-emergent pesticide use at Carman between 2001 and 2004.

Herbicide	Crop	Date	Rate (g a.i. ha^{-1})	Pests controlled
Benomyl	Canola	5 July 2001	494	*Sclerotinia sclerotiorum*
Bromoxynil plus MCPA	Linola	5 June 2003; 25 June 2004	280 plus 280	Green smartweed, red root pigweed, volunteer canola, lambsquarter, wild buckwheat, wild mustard
Clodinafop-propargyl	Wheat	12 June 2001; 14 June 2002; 5 June 2003; 11 June 2004	56.4	Green foxtail
Glufosinate ammonium	Canola	8 June 2001; 14 June 2002; 5 June 2003; 25 June 2004	500	Green foxtail, wild mustard, lambsquarter, green smartweed, wild buckwheat, red root pigweed
MCPA amine	Linola	21 June 2001; 14 June 2002	285	Lambsquarter, wild mustard, red root pigweed, green smartweed
Propanil	Linola	21 June 2001; 14 June 2002	988	Green foxtail
	Oat	8 June 2001; 14 June 2002; 5 June 2003		
Sethoxydim	Linola	5 June 2003; 25 June 2004	144	Green foxtail, volunteer wheat
Thifensulfuron methyl plus tribenuron methyl	Oat	8 June 2001; 14 June 2002; 5 June 2003; 11 June 2004	9.9 plus 4.95	Green smartweed, volunteer canola, wild buckwheat, lambsquarter, wild mustard, red root pigweed
	Wheat	12 June 2001; 14 June 2002; 5 June 2003; 11 June 2004		
Vinclozolin	Canola	4 July 2003; 15 July 2004	15	*Sclerotinia sclerotiorum*

production. No post-emergent herbicides were used on alfalfa. Alfalfa was terminated in its second year of production by spraying with 3.7 liters ha^{-1} glyphosate a few days prior to the second or third cut. All plots were sprayed in September after harvest with 3.7 liters ha^{-1} glyphosate and 1.0 liter ha^{-1} MCPA amine. Canola was sprayed for *Sclerotinia sclerotiorum* with benomyl at 0.494 kg a.i. ha^{-1} in 2001 and vinclozolin at 0.15 kg a.i. ha^{-1} in 2003 and 2004.

Sampling

Seed crops were harvested with a Massey Ferguson 8-XP small plot combine (Kincaid Equipment Manufacturing, Haven, Kansas). Most crops were swathed before combining, with the exception of wheat and oats in some years (Table 2). Straw was chopped and spread back onto the plot area, with the exception of the linola straw which was dropped unchopped behind the combine and removed from the plots. Grain was cleaned, weighed and dried at 65°C for 72 hours, so that yield data could be expressed on a 0% moisture basis. Total biomass was measured to determine the productivity of each cropping system. Total dry matter (DM) production for PFP crops was determined in 2001, 2003 and 2004 from two, 1-m^2 randomly selected quadrats within each subplot prior to harvest operations. Crop and weed plants were separated, dried at 65°C for 72 hours and weighed to determine dry material yield for crop and weeds.

In its establishment year, the first alfalfa harvest was timed to minimize weed seed rain. If the season permitted, a second cut was taken. In its second year of production, alfalfa harvest was timed to coincide with 5–10% bloom. Alfalfa was harvested twice in all years except 2001, when alfalfa was harvested three times. Dry matter yield was determined at each alfalfa harvest prior to mechanical haying from two, 1-m^2 quadrats per plot. The samples of first-year alfalfa were sorted into alfalfa and weed components to determine the effect of the previous PFP crop(s) on alfalfa and weed yield.

Weed seedlings were counted in all plots, within three, 25 × 25 cm quadrats per plot, just prior to the time of in-crop herbicide application for the non-PFP plots. Weed seedlings were not enumerated in the second year of alfalfa production because weeds were difficult to identify in the thick alfalfa stand.

Data analysis

Analysis was conducted using Statistical Analysis System (SAS) version 8.2 for Windows (SAS Institute Inc. Cary, North Carolina). The experiment was analyzed as a randomized complete block using analysis of variance (ANOVA) procedures to detect significance ($P < 0.05$). ANOVA was performed within each crop type. Homogeneity of error variance was tested using Bartlett's test. Log transformations were used on data when variances were non-homogeneous, and transformed data were tested for homogeneity of variance using Bartlett's test.

Data were not included in the analysis when treatments were not complete. For example, in 2003, wheat yield was not included in the analysis for the PFP linola–PFP oat–canola–wheat rotation because PFP linola was not grown in 2000, therefore, 2 years of PFP had not yet occurred before wheat.

Results and Discussion

Environmental conditions

The mean monthly air temperature at Carman between 2000 and 2003 was very similar to the 30-year average for that region (Table 4). Two exceptions include June 2000, when air temperature was 2.6°C less than the 30-year average, and May 2002 when air temperature was 3.4°C less than the 30-year average. In 2004, however, monthly temperatures were well below that of the 30-year average. Total monthly precipitation between 2000 and 2004 at Carman varied a great deal from the 30-year average. The most notable deviations from the 30-year average were May 2004 (85.6 mm greater), July 2001 (115 mm greater), June 2002 (66 mm greater) and August 2002 (63 mm greater).

Weed population dynamics

The effect of PFP on weed population dynamics was assessed by measuring spring weed density prior to treatment with in-crop herbicide in both the PFP (linola and oat) and post-PFP (canola, wheat and alfalfa) crops. One notable general observation was that weed density increased over the 5 years of the experiment (Table 5). This increase was attributed to weather patterns and not the treatments. For example, in 2002 and 2003, significant rain events occurred several days prior to weed enumeration, potentially stimulating weed emergence (data not shown).

Six weed species were identified in this study: green foxtail, red root pigweed, lambsquarter, wild buckwheat, green smartweed (*Polygonum* spp.) and dandelion (*Taraxacum officinale* Weber in Wiggers). Green foxtail, and red root pigweed were the dominant species amongst treatments (data not shown).

PFP phase of crop rotation. Weed density in linola was the same for all treatments in the first 4 years of the study (Table 5). In the fifth year (2004), however, weed density in linola was higher in the forage rotation when compared to the annual grain rotation, regardless of whether it was PFP or treated with herbicide. Poor weed suppression with alfalfa in 2004 likely reflects the weed species present. Alfalfa hay crops in rotation are known to effectively reduce seed or propagule-limited weed species such as wild oat (*Avena fatua* L.) and Canada thistle (*Cirsium arvense* L.)[17,20], but suppression of other weed species, such as green foxtail[17], red root pigweed and lambsquarter[20], is less effective. In this experiment, green foxtail and red root pigweed, not wild oat or Canada thistle, were the dominant weeds, thus reducing alfalfa's weed control impact (data not shown). Furthermore, in this experiment, alfalfa was grown without the use of any post-emergent herbicide, which may have further contributed to the increase in weeds in this rotation. Thus, when weeds such as green foxtail and red root pigweed are present, linola in the forage rotation may not be well positioned for herbicide use reduction, because weed pressure would be too high. It would be important to the success of PFP linola for spring weed density to be low, as linola is not a very competitive crop with weeds[21,22].

Weed density in oat was higher when it followed PFP linola in 2002, in both the annual and forage rotations (Table 5). In 2004, however, weed density in PFP oat was

Table 4. Monthly mean air temperature (°C) and total monthly precipitation (mm) at Carman, Manitoba in 2000 to 2004, and the 30-year average[1].

	Temperature (°C)						Precipitation (mm)					
	2000	2001	2002	2003	2004	30-year avg.	2000	2001	2002	2003	2004	30-year avg.
May	11.5	12.8	8.2	12.2	7.8	11.6	55.0	52.6	40.6	80.2	139.6	54.0
June	14.6	16.2	17.7	16.6	14.5	17.1	93.6	41.2	141.0	90.0	32.4	75.0
July	18.9	19.8	20.3	19.2	17.9	19.8	46.8	192.5	49.4	56.4	50.2	77.0
August	18.7	19.5	17.8	20.7	14.0	18.4	86.0	22.2	129.2	70.8	78.0	66.0
September	11.8	13.4	13.6	12.4	14.1	12.5	40.0	13.6	21.0	36.2	86.8	49.0
Average	15.1	16.3	15.5	16.2	13.7	15.9	321.4	322.1	381.2	333.6	387.0	334.0

[1] Environment Canada.

Table 5. Total weed seedling density (seedlings m^{-2}) as influenced by Pesticide Free Production (PFP) and crop rotation at Carman, Manitoba.

Rotation	2000	2001	2002	2003	2004
			Linola		
PFP linola[1]–PFP oat–canola–wheat	–	42	11	97	309*bc*
Linola–PFP oat–canola–wheat	–	24	7	100	162*cd*
Linola–oat–canola–wheat	18	8	77	170	87*d*
PFP linola–PFP oat–alfalfa–alfalfa	–	7	40	248	593*a*
Linola–PFP oat–alfalfa–alfalfa	19	9	29	269	548*ab*
Linola–oat–alfalfa–alfalfa	–	18	23	174	456*ab*
			Oat		
PFP linola–**PFP oat**–canola–wheat	–	–	852*a*	4040	552*c*
Linola–**PFP oat**–canola–wheat	–	24	368*b*	2068	470*c*
Linola–**oat**–canola–wheat	20	32	195*b*	2897	1330*b*
PFP linola–**PFP oat**–alfalfa–alfalfa	–	–	813*a*	2056	2772*a*
Linola–**PFP oat**–alfalfa–alfalfa	–	17	184*b*	1064	707*c*
Linola–**oat**–alfalfa–alfalfa	23	37	183*b*	972	571*c*
			Canola		
PFP linola–PFP oat–**canola**–wheat	–	–	–	777	1300*a*
Linola–PFP oat–**canola**–wheat	–	39	152	485	1179*a*
Linola–oat–**canola**–wheat	14	26	10	259	324*b*
			Wheat		
PFP linola–PFP oat–canola–**wheat**				–	490*b*
Linola–PFP oat–canola–**wheat**	–	–	18	622	584*b*
Linola–oat–canola–**wheat**	14	14	16	522	1074*a*
			Alfalfa		
PFP linola–PFP oat–**alfalfa**–alfalfa	–	–	–	1199	611*a*
Linola–PFP oat–**alfalfa**–alfalfa	–	16	44	1165	1412*a*
Linola–oat–**alfalfa**–alfalfa	12	19	6	1091	130*b*

[1] Weed seedling density is for the bold-faced and underlined crop.
Means followed by different letters are considered to be significantly different ($P < 0.05$).

only higher after PFP linola in the forage rotation. As with the linola, it would appear that the herbicide options available for canola and wheat in the annual rotation are more effective at reducing populations of green foxtail and red root pigweed, when compared to the weed suppression effects of an unsprayed alfalfa hay crop. Based on the weed density information, this study suggests that both linola and oat would be better positioned for PFP in the annual crop rotation than in the forage rotation. Ball[13] concluded that crop rotation was the most dominant factor influencing weed population dynamics, due in part to the effect of herbicide use on each crop in the weed seedbank.

Post-PFP phase of crop rotation. Canola and alfalfa were the first crops in the post-PFP phase for the annual and forage rotations, respectively. Weed density was higher as a consequence of PFP in the first year of the post-PFP phase in 2004 only (Table 5). When canola or alfalfa followed 1 or 2 years of PFP, weed density was higher in these crops when compared to canola and alfalfa following herbicide-treated crops.

Wheat and alfalfa were the second crops in the post-PFP phase of the annual and forage rotations, respectively. Inclusion of PFP in the crop rotation had no effect on weed density in the second crop of the post-PFP phase of either rotation. It would appear from these results that weed populations following the inclusion of PFP in a crop rotation will be only be higher for the first year after PFP.

Dry matter production in PFP phase of crop rotation

Crop and weed DM production of PFP crops was measured prior to grain harvest in 2001, 2003 and 2004. From these measurements, total DM production and the ratio of crop DM production to total DM production (crop DM:total DM) was calculated to determine the weed competition against the crop (Table 6).

As expected, the crop DM:total DM ratio was significantly lower for PFP linola than for herbicide-treated linola, regardless of crop rotation, indicating that weeds comprised a larger proportion of total biomass when grown as PFP than when linola was treated with herbicide. In 2001, however, the crop DM:total DM ratio did not differ between PFP linola and herbicide-treated linola in the annual rotation. In this case crop, the DM:total DM ratio was low even when linola was treated with herbicide. In

Table 6. Total dry matter yield (kg ha^{-1}) for the Pesticide Free Production (PFP) phase of the Pesticide Free Production crop rotation study 2001–2004.

	2001		2003		2004	
Rotation	**Total**	**Crop DM:Total DM**	**Total**	**Crop DM:Total DM**	**Total**	**Crop DM:Total DM**
PFP linola[1]–PFP oat–canola–wheat	4736*b*	0.69*b*	7404*a*	0.66*b*	6580*bc*	0.74*b*
Linola–PFP oat–canola–wheat	4460*bc*	0.78*ab*	5417*c*	0.98*a*	5511*d*	0.95*a*
Linola–oat–canola–wheat	4334*c*	0.69*b*	6111*bc*	0.98*a*	6121*cd*	0.99*a*
PFP linola–PFP oat–alfalfa–alfalfa	5600*a*	0.72*b*	7278*ab*	0.71*b*	7922*a*	0.66*b*
Linola–PFP oat–alfalfa–alfalfa	4107*c*	0.93*ab*	6165*bc*	0.99*a*	7524*ab*	0.93*a*
Linola–oat–alfalfa–alfalfa	4148*c*	0.99*a*	6134*bc*	0.99*a*	7298*ab*	0.97*a*
PFP linola–**PFP oat**–canola–wheat	9098*b*	0.99	11,094	0.96*ab*	10,191	0.97*a*
Linola–**PFP oat**–canola–wheat	10,010*a*	0.98	11,342	0.94*b*	9900	0.99*a*
Linola–**oat**–canola–wheat	7926*c*	0.99	12,299	0.99*a*	13,192	0.98*a*
PFP linola–**PFP oat**–alfalfa–alfalfa	9425*ab*	0.98	10,417	0.95*b*	9850	0.92*b*
Linola–**PFP oat**–alfalfa–alfalfa	9240*ab*	0.99	11,170	0.94*b*	10,033	0.98*a*
Linola–**oat**–alfalfa–alfalfa	7756*c*	0.99	10,870	0.99*a*	15,563	0.99*a*

[1] Crop and weed dry matter is for the bold-faced and underlined crop.
DM, dry matter.
Means in columns with different letters are considered to be significantly different ($P < 0.05$).

2001, the crop DM:total DM ratio for herbicide-treated linola following alfalfa was higher than the ratio for PFP linola following alfalfa. This suggests that herbicide was more effective at reducing weeds after alfalfa than after wheat in this year. In a survey of Canadian prairie farmers, respondents indicated less need for herbicide in crops grown after perennial forages[16]. Total DM was lower in 2001 than in other years, which may be why this trend did not continue in 2002 to 2004.

In 2003, the crop DM:total DM for PFP oat was less than that of herbicide-treated oat, regardless of crop rotation. In 2004, however, only PFP oat following PFP linola in the forage rotation had a significantly lower crop DM:total DM ratio when compared with herbicide-treated oat. Weed seedling density was also significantly higher for PFP oat following PFP linola in the forage rotation in 2004 (Table 5). Again, this may be attributed to the fact that a 2-year stand of alfalfa was not effective in suppressing green foxtail and red root pigweed, the dominant weeds in this study.

Crop yield

PFP phase of crop rotation. Of the two PFP grain crops, only linola yields were affected by the PFP practice. PFP linola consistently yielded less than herbicide-treated linola in the forage rotation, but not in the annual grain rotation (Table 7). One reason for lower PFP linola yields than herbicide-treated linola after alfalfa may be the higher weed pressure in the forage rotation. For example, in 2004, weed DM in PFP linola constituted 34% of the total biomass harvested in the forage rotation, compared with 26% in the annual rotation (Table 6).

PFP linola did not always yield less than herbicide-treated linola in the annual rotation, however (e.g. 2002 and 2004). In 2004, even though the crop DM:total DM ratio was significantly lower for PFP versus herbicide-treated linola, grain yield was no different between treatments. A possible explanation for the lack of yield decline in the face of greater weed competition under PFP may be related to the water regime that year. It is known that the competitive stress of weeds is often reduced when growth resources, such as water, are in abundance[23]. Moisture availability was, in fact, excellent during the 2004 season (Table 4).

In this experiment, oat did not require post-emergent herbicide for economic grain yield (Table 7). Even when PFP oat followed PFP linola (2002, 2003 and 2004), oat yielded the same as herbicide-treated oat despite very high weed densities in the oat crops (Table 5). Oat is very competitive with weeds, which appears to have contributed to its success as a PFP crop[24]. Stevenson et al.[11] found that improving crop competition through increasing seeding rates allowed the periodic removal of herbicide in cereals without incurring short-term yield loss. Oat yield, however, was affected by crop rotation in 2003 (Table 7). Yield of oat was less in the forage rotation than the annual grain rotation. Alfalfa has deep roots and a high water demand[25], therefore, it was speculated that there may have been less soil water available for crop growth when oat followed 2 years of alfalfa in 2003. Conditions in 2003 were hot, with only average precipitation (Table 4).

Post-PFP phase of crop rotation. Grain yield of crops appearing in the rotation after PFP were not negatively affected by inclusion of PFP in the rotation, despite sometimes higher spring weed populations in these crops. For example, although weed density in canola following 1 or 2 years of PFP was higher than weed density in canola following herbicide-treated crops (Table 5), canola yield was the same for all treatments. Wheat was the second

Table 7. Grain and forage yield (kg ha^{-1}) for the Pesticide Free Production crop rotation study 2000–2004.

Rotation	2000	2001	2002	2003	2004
			Linola		
PFP linola[1]–PFP oat–canola–wheat	–	672*b*	1139*bc*	1250*cd*	1134*bc*
Linola–PFP oat–canola–wheat	–	1106*a*	3378*a*	1700*a*	1557*a*
Linola–oat–canola–wheat	–	1026*a*	2440*ab*	1629*ab*	1299*ab*
PFP linola–PFP oat–alfalfa–alfalfa	–	1030*a*	1461*bc*	1040*d*	781*c*
Linola–PFP oat–alfalfa–alfalfa	–	1130*a*	2831*a*	1430*abc*	1192*abc*
Linola–oat–alfalfa–alfalfa	–	1284*a*	3180*a*	1347*bc*	1199*ab*
			Oat		
PFP linola–**PFP oat**–canola–wheat	–	–	4277	4962*a*	4894
Linola–**PFP oat**–canola–wheat	5241	3306	4287	4974*a*	5103
Linola–**oat**–canola–wheat	5017	3007	3389	4951*a*	4253
PFP linola–**PFP oat**–alfalfa–alfalfa	–	–	3781	3794*b*	4622
Linola–**PFP oat**–alfalfa–alfalfa	4948	2851	3376	4186*b*	4499
Linola–**oat**–alfalfa–alfalfa	4709	3196	3601	4149*b*	4933
			Canola		
PFP linola–PFP oat–**canola**–wheat	–	–	–	2552*a*	3288
Linola–PFP oat–**canola**–wheat	–	1957	1843	2494*a*	3537
Linola–oat–**canola**–wheat	–	2390	1615	1745*b*	3316
			Wheat		
PFP linola–PFP oat–canola–**wheat**	–	–	–	–	4787
Linola–PFP oat–canola–**wheat**	–	–	3010	4454	4735
Linola–oat–canola–**wheat**	3566	2271	2998	4580	4535
			Alfalfa (year 1)		
PFP linola–PFP oat–**alfalfa**–alfalfa	–	–	–	6189	3746
Linola–PFP oat–**alfalfa**–alfalfa	–	12,241	5130*a*	6418	3967
Linola -oat–**alfalfa**–alfalfa	5804	10,155	4513*b*	5932	5435
			Alfalfa (year 2)		
PFP linola–PFP oat–alfalfa–**alfalfa**	–	–	–	–	9557
Linola–PFP oat–alfalfa–**alfalfa**	–	–	11,394	11,988	9667
Linola–oat–alfalfa–**alfalfa**	5589	8925	12,189	13,516	9260

[1] Grain or forage yield is for the bold-faced and underlined crop.
Means with different letters are considered to be significantly different ($P < 0.05$).

post-PFP crop in the annual rotation. Herbicide use in the canola crop prior to wheat appeared sufficient to control any extra weeds that may have occurred due to inclusion of 1 or 2 years of PFP in the rotation; thus, PFP had no negative effect on wheat yield in this experiment (Table 7). It is significant to note that wheat and canola crops following PFP crops did not receive more herbicide than those in the non-PFP system. The overall PFP goal of herbicide reduction was therefore achieved. The farmers that participated in the on-farm PFP study also indicated that they did not use any more herbicide than they normally would have to control weeds after PFP[6].

The post-PFP phase of the forage rotation consisted of 2 years of alfalfa. Glyphosate was used for weed control prior to alfalfa emergence, but no post-emergent herbicide was used for weed control. When establishing alfalfa without a companion crop, it is typical in Manitoba to time the first harvest to remove weeds before weed seed rain. In this study, total biomass yield was not affected by including PFP crops in the rotation (Table 6), but forage composition was. For example, although there was no significant difference in total forage biomass in 2004, the treatments following PFP crops had significantly less alfalfa than those that followed herbicide-treated crops (data not shown). Weeds comprised 82% of total forage yield following 2 years of PFP, 86% following 1 year of PFP and 64% following herbicide-treated crops. A negative effect of these weeds is that they can influence forage quality. Many of the weed species in this study have a similar or greater crude protein and digestibility as that of bromegrass (*Bromus inermis* L.)[26]. Forage quality testing may be necessary for diet formulation when feeding very weedy forage. If broadleaved weeds such as red root pigweed and lambsquarter comprise a significant proportion of the forage, anti-quality factors such as nitrates may also be a concern[27]. Total forage production for the second year of alfalfa production was the same whether alfalfa followed PFP or herbicide-treated crops. Weed DM production was not measured in the second year of alfalfa production because weeds were negligible in all treatments.

Summary and Conclusions

This study provided information on the effects of PFP on no-till crop yield and weed population dynamics in PFP and post-PFP crops. In this experiment, oat was a more successful PFP crop than linola. Weed density in linola was low relative to the other crops in the rotation, but weeds often competed effectively with PFP linola for resources, as evidenced by a lower crop DM : total DM ratio at harvest. In the fifth year of the experiment, spring weed populations in linola were higher in the forage rotation than the annual rotation. PFP linola yield was often lower than herbicide-treated linola yield, particularly in the forage rotation. This yield penalty was attributed to higher weed densities after PFP. Even though spring weed density was often very high in oat, particularly when PFP oat followed PFP linola, PFP oat yielded the same as herbicide-treated oat in all years of the study, because oat is a more aggressive competitor with weeds than linola[24].

Including either one or two PFP crops in the rotation did not negatively affect the yield of post-PFP crops, despite sometimes increasing post-PFP weed population densities. The lack of grain yield decline in the face of higher weed populations (e.g. canola in 2004) indicates that the combination of fall and spring treatment with glyphosate and one in-crop herbicide treatment in non-PFP grain crops was sufficient to protect crop yield. This information clearly shows that PFP crops really did allow a genuine decline in overall rotational herbicide use in this study. The number of herbicide applications was reduced by 8–17% in the annual grain rotation, and by 11–22% in the forage rotation, depending on whether PFP occurred once or twice in the rotation. Annual grain-based and integrated grain- and forage-based rotations are practiced on approximately 30 million hectares in the Canadian prairies. A reduction in the number of herbicide applications by 8–22% is significant over this large area. When alfalfa was the post-PFP crop, total forage yield was unaffected by PFP; however, post-PFP alfalfa contained more weed biomass than alfalfa in the non-PFP system.

Alfalfa hay crops in the present study were not as effective as herbicide-treated wheat and canola in lowering weed pressure. The types of weed species encountered in this study strongly influenced the effectiveness of alfalfa in facilitating PFP, since major weeds in the study were not controlled by alfalfa[17]. Had wild oat or Canada thistle been major weeds, alfalfa would likely have played a stronger role in reducing post-PFP weed densities. In-crop herbicide use during the alfalfa establishment year may also have reduced post-PFP weed populations. Such a system would still allow fewer herbicide applications than the annual rotation where both non-PFP crops were treated with in-crop herbicides.

Results of this study confirm observations from on-farm investigations[6] and field experiments[11], where skipping herbicide application in certain years was found not to negatively affect the performance of following crops.

This paper presents data from the first 5 years of a long-term rotation study; therefore, the results of this research are preliminary. The results indicate that PFP is a simple way to reduce herbicide use in no-till crop production[8], but that selection of a more competitive PFP crop and choice of crops in the rotation are important considerations for successful herbicide reduction. This rotation study will continue as a part of ongoing research under a pesticide-reduction initiative.

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Internationalization of the organic fruit market: The case of Washington State's organic apple exports to the European Union

Gregory M. Peck[1,*], Preston K. Andrews[1], Cindy Richter[2], and John P. Reganold[3]

[1]Department of Horticulture and Landscape Architecture and [3]Department of Crop and Soil Sciences, Washington State University, Pullman, Washington, 99164 USA. [2]Pacific Organic Produce, San Francisco, California, 94109 USA.
*Corresponding author: gpeck@wsu.edu

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Abstract

Production of some organic commodities, such as apples, is heavily concentrated in the United States (US), with Washington State being the leading US producer of organic apples. In 2003, there were 4047 ha of certified organic apple orchards in Washington State, an all-time high and a more than tenfold increase since 1989. But this growth has not occurred without difficulties. Washington State's organic apple growers have encountered international supply and demand pressures forcing them to seek new markets, such as the European Union (EU). In this paper, we explore the complexities of the international marketing of organic fruit, using organic apple production in Washington State and market opportunities for this organic fruit in the EU, as a case study. We find that as a result of the expansion of organic apple plantings in Washington State, there has been a decrease in the price premiums, which traditionally offset the greater costs of organic production and which originally motivated many Washington growers to certify their apple orchards. We also find that increased demand for organic fruits in the EU has been outpacing supply, making EU member states the most important export market for Washington's organic apples. However, despite the unification of US standards by the US Department of Agriculture (USDA) and an overriding EU standard, an entanglement of regulatory bodies from around the world is involved in the certification of organic products. For example, growers and marketers may have to interact with as many as six different regulatory bodies in order to export organic produce from the US to the EU. This study shows that while the EU market remains a promising destination for US organic apples, organic growers and marketers must plan ahead and thoroughly understand the multitude of regulations involved in the international trade of organic fruits.

Key words: apples, certification, European Union, exports, organic, regulations, Washington State

Introduction

Products from organic farming systems continue to gain consumer acceptance in the marketplace, and thus the number of farmers converting to organic production and the total land area planted with organic crops have shown tremendous growth. However, at this time there are few published reports on the international trade of organic products, with most of the available information on the international organic market either proprietary or published through Web sites that have little to no peer review. The lack of a coherent internationally accepted definition for organic products, and the lack of segregated data collection from nations for the organic sector, further complicate the analysis of the global organic market and highlight the variability in reported production and sales statistics.

Yet, with more than 100 countries producing organically certified products in 2002 and worldwide consumption of organic products estimated to be between US$19 billion and US$26 billion in 2001[1,2], it is clear that the organic marketplace has internationalized. Once only available from small or direct-market venues, such as natural food stores and farmers' markets, organic products are now sold widely at large natural foods retailers, commercial supermarkets and discount retailers[3]. Demand for organically produced food grew by 20% annually in the US, and even faster in

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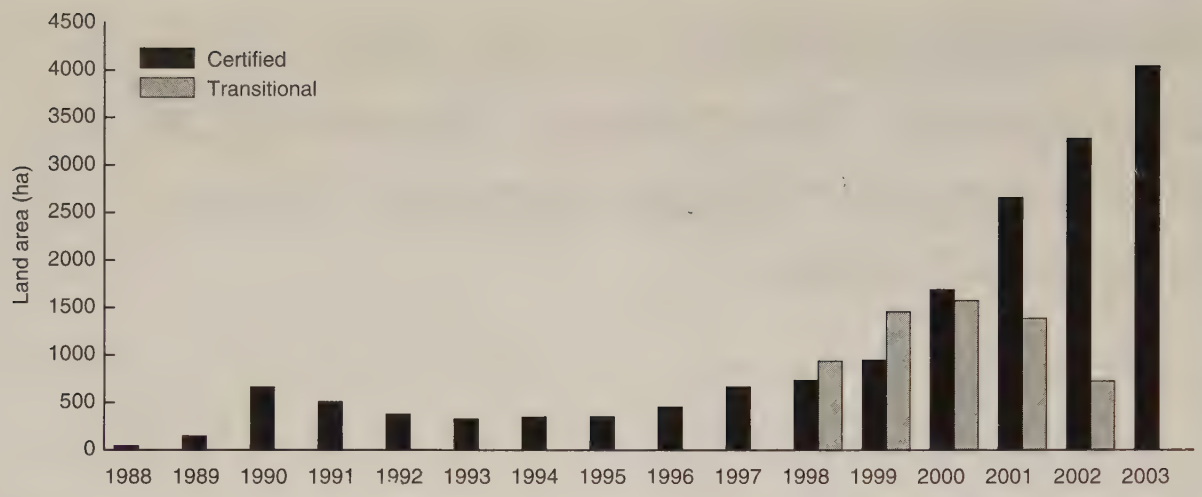

Figure 1. Area of certified organic and transitional orchards in Washington State from 1988 to 2003[15,16]. 2003 data are projected, not actual.

much of Europe, through the 1990s[3–5], with US and EU consumers accounting for more than 90% of the world's organic food and beverage sales[2]. This demand has been bolstered by recent food safety concerns, such as mad cow disease, foot-and-mouth disease, the implications of genetically engineered crops and concerns over the long-term health and environmental effects of synthetic fertilizers and pesticides[6,7]. In 2001, the US Department of Agriculture (USDA) reported over 528,000 ha of certified organic cropland (not used for animal husbandry) in the US, an increase of 53% since 1997, but representing just 0.3% of all US farmland[8]. The EU was estimated to have more than 4 million hectares of organically certified land in 2001[5], but it is not known how much of this land was used for crop production. From an environmental perspective, this growth is a favorable prospect, since organic systems have been shown to be more environmentally sustainable and energy efficient[9,10]. Consumers interested in purchasing organic food have also benefited, because the diversity and quality of organic products have improved dramatically[11].

Organic apple sales have benefited from the overall increase in organic market share and production, as fruit and vegetables hold the largest market share of organic sales[12]. While apples are produced organically on every continent, organic apple production is heavily concentrated in the US, with Washington State being the leading US producer of organic apples[13]. Organic apple orchards are a feasible alternative to conventional apple orchards in Washington State, where the dry climate limits yield losses from fungal pathogens, particularly apple scab (*Venturia inaequalis*). Nevertheless, like their conventional counterparts, Washington State's organic apple growers face lower returns and slimmer profit margins as both domestic and international competition has become increasingly fierce.

At the same time as Washington State has seen an increase in organic apple production, EU countries with a high volume of organic sales, such as France, Germany and the United Kingdom (UK), are importing upwards of 90% of their organic apples. With the EU experiencing an increase in the consumer demand for organic apples that they cannot fulfill, the EU seems an obvious destination for organic apples grown in Washington State. However, the existence of many organizations involved in certifying organic produce domestically and internationally has made it extremely difficult for growers, marketers and consumers to understand the acceptable organic standards both within their own country and abroad. When Washington's apple growers and fruit brokers target EU organic buyers, differences between US, EU and international regulations may prohibit organic fruit from entering the EU marketplace.

The purpose of this paper is to explore the complexities of the international organic fruit market by using organically produced apples in Washington State and market opportunities for this organic fruit in the EU as a case study. We will discuss Washington State's organic apple production market trends, the EU demand for organic apples and the multitude of organic certification bodies and their regulations in the US and EU. Data on the international organic apple market have been gathered from international trade organizations, official country Web sites, and Pacific Organic Produce, which packs (under a partnership with Pac Organic Fruit, LLC in George, Washington) and markets approximately 20% of Washington's organic apples to both domestic and foreign destinations.

Washington State Market Trends

In 1990, the year after the plant bioregulator Alar™ (daminozide) was implicated as a potential carcinogen[14], a spike in organic apple production occurred in Washington State, where Alar™ was commonly applied to conventional apple orchards (Fig. 1). Washington State's organic apple

plantings continued their expansion through the 1990s and reached 4047 organically certified hectares in 2003, a more than tenfold increase since 1989 (Fig. 1). This represented about 40% of total US organic apple production in 2003, and made Washington State the leading organic apple producer in the US. California had the second most organically certified hectares of apple orchards in the US, with just under 25% of the total US organic apple plantings. For Washington State, organic production (including orchards in the three-year transition to organic certification), accounted for nearly 6% of the total land planted in apples[15,16]. The total US organic pome (apples and pears) and stone (cherries, peaches, apricots and plums) fruit holdings are estimated to be over 10,000 hectares[15,16], which is between 2 and 3% of the US total for these crops[13].

Despite the increased volume of US organic apple sales, the expansion in organic apple production has saturated the US market and reduced the price premiums that originally motivated many Washington growers to certify their apple orchards. Price premiums are now highly variable, depending upon the size of the crop for a particular year and the cultivar in question (Fig. 2), and so organic certification no longer ensures profitability in Washington State's apple industry. Additionally, price premiums helped offset the greater costs of organic production, and their loss has hurt many of the small and mid-sized organic apple operations.

Lower organic price premiums can be correlated directly not only with increases in plantings and production, but also with industry consolidation[11]. As with many other commodities, large fruit-packing and marketing companies are dedicating packing plants solely to organic fruit, ensuring uninterrupted organic sales and preventing cross-contamination from conventional fruit. Pac Organic Fruit has recently forged an alliance with Snokist Growers Co-Op (Yakima, Washington), one of the largest conventional fruit-packing firms, cooperating to pack organic fruit[18]. Stemilt Growers, Inc. (Wenatchee, Washington), the largest conventional apple packer in the US, recently purchased a packinghouse that will be dedicated exclusively to organic fruit[19].

The importance of price premiums to organic growers was emphasized by the estimation in 2000 that organic 'Golden Delicious' orchards in Washington State needed 12–14% premiums to match the breakeven point (when revenues equal the investment cost over the life of an orchard) of conventional orchards planted with the same cultivar[9]. In that year, 'Golden Delicious' apples received a 16% free on board (FOB) price premium over conventional 'Golden Delicious' prices, and the 2001 harvest received 23%, both years down from the record high in 1997 of 120% (Fig. 2). Although organic premiums for 'Golden Delicious' apples have somewhat increased since 2000 (Fig. 2), these orchards are still in danger of becoming economically less sustainable.

As with the conventional market, organic apple prices are cultivar specific. For example, organic 'Golden Delicious' apples received some of the lowest price premiums in 2000, followed by 'Red Delicious', while 'Fuji' and 'Gala' received a premium of approximately 50%, and 'Pink Lady', a cultivar in high demand, received an average premium of 91% (Fig. 2). The declining trend for 'Golden Delicious' price premiums might apply to other apple cultivars in the future if production of those cultivars continues to soar. Clearly, the US organic apple market is not growing at the same rate as the production of organic apples, and thus export markets, such as the EU, must be explored in order to sell the current volume of organic apples produced and for organic apple production to continue its expansion in Washington State.

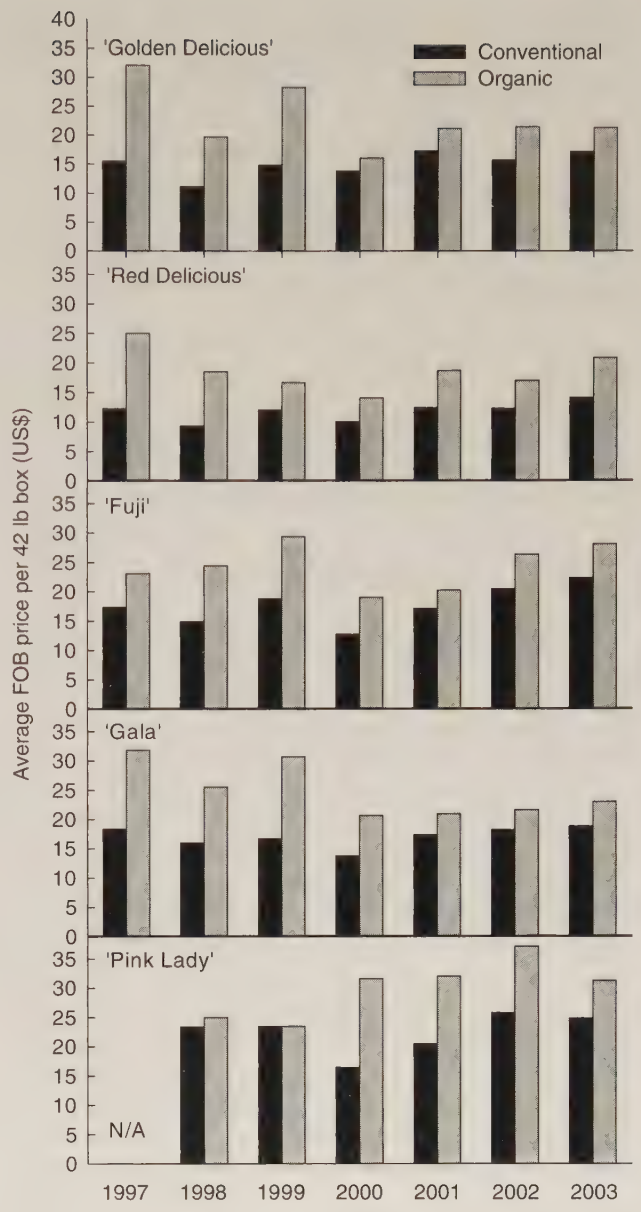

Figure 2. Annual (September through August) average market price (FOB, free on board) of five apple cultivars, representing the majority of Washington State's apple sales[17].

Table 1. Organic sales, production and imports for key European Union member states and the United States.

Country	Total organic retail sales for 2003 (million US$)	Total land area in organic production for 2003 (hectares)	Domestic organic fruit production; year	Organic fruit and vegetable sales (million US$; year)	Apple imports (mt; year)	Main importer of apples
Austria	325–375[2]	285,500[5]	6,000 mt; 1999[21]	29; 2000[21]	400; 1999[21]	Italy[21]
Belgium	200–250[2]	22,410[5]	612 ha; 1999[21]	34; 2000[21]	650–700; 2000[21]	Netherlands, Argentina, New Zealand[21]
Denmark	325–375[2]	174,600[5]	197 ha (of which 66 are apples); 1999[21]	N/A. 2000–2500 mt; 2000[21]	1750–2250; 2000[21]	Italy, Germany, Netherlands, Argentina, US, New Zealand[21]
France	1200–1300[2]	419,750[5]	8210 ha (of which 748 are in apples); 2000[21]	170; 1998[21]	1814; 1999[21]	Italy[21]
Germany	2800–3100[2]	632,165[5]	2710 ha (of which 393 are in pome fruit); 1997/98[21]	378; 2000[21]	3000; 2001[21]	Italy, Argentina, New Zealand[21]
Italy	1250–1400[2]	1,230,000[5]	474,000 mt; 2000[21]	264; 2000[21]	495; 2000[21]	Argentina[21]
Sweden	350–400[2]	193,611[5]	65 ha; 2000[21]	31; 2000[21]	850–900; 2000[21]	Italy, France, Argentina, Chile[21]
The Netherlands	425–475[2]	38,000[5]	4000 mt (of which 2500 are apples) 260 ha (of which 180 are apples); 1999[21]	N/A. 40,000–45,000 mt; 1999[21]	2500–3500; 2000[21]	Chile, Argentina, Brazil[21]
United Kingdom	1550–1750[2]	679,631[5]	2951 mt (of which 1000 are apples); 1998/99. 811 ha; 2002[21,22]	267; 1999[21]	N/A. 90% of organic apples are imported[20]	US, Israel, Egypt, Turkey, other EU member states[21]
United States	11,000–13,000[2]	950,000[23]	10,010 ha; 2001 (of which 4047 are apples within Washington State); 2003[15,16]	2250[3]	N/A	N/A

European Demand

Janice Zygmont[20], formerly of the USDA Foreign Agricultural Service, stated that Europe was the biggest importer of US organic goods in 1999, with the UK being the leading importer in Europe, accounting for US$32.5 million, followed by Germany at more than US$22 million. In the past few years, demand for organic food in the UK has increased at 40% a year, outpacing supply, which is growing at 25% annually[20]. Of that growth in sales, fresh produce accounted for about 50% of total organic sales. This large discrepancy between supply and demand represents a significant market potential for US fruit. However, organic markets in individual EU member states are extremely variable, growing anywhere from 0 to 40% annually[5,20]. Additionally, it is difficult to assess the market for individual commodities as no central clearinghouse for organic sales information has been established within the EU. Thus, each EU country needs to be evaluated individually.

The largest organic apple markets in the EU are Denmark, France, Germany, The Netherlands, and the UK (Table 1). This is backed by sales figures from Pacific Organic Produce, for which the UK represents their largest EU export destination, followed by Germany and then The Netherlands. While most EU member states are producing organic apples, only Italy appears to produce nearly enough organic apples to meet domestic demand, importing only about 495 mt of organic apples, mostly from the southern hemisphere during the winter months (Table 1). Italy was also cited as a main importer of organic apples from Austria, Denmark, France, Germany and Sweden (Table 1). The UK is probably the largest export destination for US organic apples, with imports accounting for over 90% of all

organic apples sold in the UK. According to one industry source, Washington State's organic apples represented one-third of all organic apples imported into the UK[24]. With Denmark, France, Germany, The Netherlands and the UK each importing at least 1500 mt of organic apples (Table 1), it is clear that the EU has the demand to consume Washington State's supply of organic apples. However, at this point, only Denmark and the UK consider the US to be a main supplier of organic apples (Table 1).

Certification and Labeling

Given the range of practices used in organic farming systems in both the US and the EU, producers and marketers need to guarantee that their products' quality and authenticity are representative of consumer expectations. Differences in geography, cultivars, rootstocks, soils, microclimate and growers' personal preferences determine the production practices and materials used in organic apple orchard management. In other words, not all organic apple orchards are managed alike, just as not all conventional apple orchards are managed alike. Thus, standards have been developed in order for organic producers to verify their authenticity and to develop confidence in the entire supply chain to the consumer[25]. Certification standards allow growers to market their produce under a recognized system, assuring the consumer that the products they buy follow specific and verifiable guidelines. Certification, therefore, gives a specific and legal definition for organic. The certification of organic produce can be thought of as a means of consumer protection and, in a more general sense, environmental stewardship.

A certifying agency's credibility is based upon its ability to enforce organic standards through farm inspections, careful review of farm records and management plans, and random post-harvest pesticide residue sampling. However, while pesticide residue analyses verify whether prohibited materials exist on the fruit, it is not truly possible to determine scientifically whether a product was grown organically. Indeed, cases have occurred where organically prohibited substances were detected on certified organic apples. The presence of prohibited substances in organic produce may originate from either intentional applications or inadvertently; for example, when persistent chlorinated hydrocarbon pesticide residues are absorbed by organic crops years after their application[26]. Additionally, some prohibited materials are identical to endogenously produced compounds or are highly volatile, such as the antioxidant DPA (diphenylamine), used by the conventional apple industry in Washington State to prevent superficial scald, a type of oxidative injury. Indeed, residue sampling has detected DPA on untreated organic apples[27,28]. Ultimately, organic certification depends heavily upon the integrity of the producer and the honesty of all affiliated handlers when reporting to their certifier.

In 1928, the biodynamic movement pioneered the marketing of certified food, with the first agricultural certification system called Demeter Certified Biodynamic. Nearly 40 years later, The Soil Association developed organic certification standards for the UK. In 1973, California Certified Organic Farmers (CCOF), a third-party, nongovernmental organization, became the first to certify organic farms in the US, but not until the 1980s did individual state agencies begin to certify organic produce. In 1983, Austria became the first nation in the world to develop official guidelines for organic farming[29]. Today, organic agriculture is highly regulated according to standards set by governmental, private and nonprofit organizations (Table 2). The multitude of organic certification bodies complicates international trade of organic products and makes the understanding of, and adherence to, the various codes essential for US apple suppliers desiring to enter the EU marketplace.

US certification and the USDA National Organic Program

In the US, national regulation of organic commodities began when the US Congress passed the Organic Foods Production Act of 1990. This Act defined organic agriculture as 'an ecological production management system that promotes and enhances biodiversity, biological cycles and soil biological activity. [Organic agriculture] is based on minimal use of off-farm inputs and on management practices that restore, maintain and enhance ecological harmony'[30]. This broad definition allows for a wide range of interpretation and management practices; therefore, in 2000 the USDA National Organic Standards Board (NOSB) passed a set of rules, collectively known as the National Organic Program (NOP), which overrode all other US certifiers' regulations and became the minimum requirements that must be followed for organic certification[25].

The final version of the NOP was approved after modifying the originally proposed standards following an unprecedented 280,000 public comments to the NOSB[31]. The most notable changes to the original rules, which brought the NOP into compliance with most EU standards, were the prohibition of food irradiation, genetically modified organisms, the use of sewage sludge in production and the use of antibiotics for livestock. The sheer number of public comments sent to the USDA demonstrates that consumer support for strong organic standards is very high. It is, after all, the consumers who are supporting the growth of this market sector.

The NOP itself does not certify individual products or growers, but sets guidelines with which other certifying agencies, such as Washington State Department of Agriculture (WSDA) Organic Food Program (OFP), Quality Assurance International (QAI), CCOF, or the Organic Crop Improvement Association (OCIA) must comply. To date, the USDA has accredited 90 organizations,

Table 2. Organizations and regulations involved in the international organic fruit market.

Full name	Acronym	Function
Basic Standards of Organic Agriculture	BSOA	IFOAM's certification standards
California Certified Organic Farmers	CCOF	Private certifier located in Santa Cruz, CA
Codex Alimentarius: Production, Processing, Labeling and Marketing of Organically Produced Foods		International standard set by United Nations Food and Agriculture Organization (FAO) and World Health Organization (WHO)
Commission Regulation 1788/2001	EC1788/2001	Certificate of Inspection for importing organic products into the EU
Demeter Certified Biodynamic		International biodynamic certification
Department for Environment, Food and Rural Affairs	DEFRA	Governmental department that sets organic policy for the UK
Euro-Retailer Produce Working Group: Good Agriculture Practices	EUREP-GAP	Private international farming standard
European Economic Community 2092/91	EEC 2092/91	EU's organic farming policy
International Federation of Organic Agriculture Movements	IFOAM	International umbrella organization for organic agriculture
International Organic Accreditation Service	IOAS	IFOAM's accredited certification body
International Organization for Standardization 65: General Requirements for Bodies Operating Product Certification Systems	ISO 65	International guidelines for certification organizations
Organic Crop Improvement Association	OCIA	Private certifier located in Lincoln, NE
Organic Materials Review Institute	OMRI	US-based nonprofit organization that maintains a materials list that is compliant with the USDA NOP
Organic Trade Organization	OTA	Membership-based association for the organic industry in North America
Quality Assurance International	QAI	Private certifier located in San Diego, CA
Soil Association		Private certifier located in Bristol, UK
USDA National Organic Program	USDA NOP	USDA Agricultural Marketing Service program for standards and certification
USDA National Organic Standards Board	USDA NOSB	Assists the USDA in developing standards for allowable substances and implementing the NOP
Washington State Department of Agriculture Organic Food Program	WSDA OFP	Washington State's certification program

54 domestic and 36 foreign[32]. The USDA does have some enforcing power with the ability to impose a civil penalty of up to US$10,000, which 'can be levied on any person who knowingly sells or labels as organic a product that is not produced and handled in accordance with the NOP's regulations'[33]. However, the USDA relies primarily upon its accredited certifiers for surveillance and enforcement of the NOP.

One of the original goals of the NOP was to facilitate bilateral trade through international certifiers by providing uniform standards for foreign buyers to reference when they purchase US organic goods[25]. A single national organic standard was thought to increase both domestic and foreign buyers' confidence, and therefore promote increased organic export sales. The NOP officially went into effect on 21 October 2002, at which time all domestically labeled organic produce and any products imported into the US must meet NOP guidelines and be certified by a USDA-accredited certification organization. A clause within the NOP allows a grower to forego US certification, yet still market products to an international buyer as organic if all such products are clearly labeled 'Export Only'[34]. While an 'Export Only' label would limit fruit to export markets, such as the EU, a US grower would not have to be certified by a USDA-accredited organization. However, the apples must pass the organic certification regulations of the destination EU member state and all applicable international bodies discussed below.

European certification and import regulations

As expected, each EU member state wants to assure their consumers and farmers that imported organic apples meet the same certification requirements as their own domestically grown organic apples. Each member state must comply with the European Economic Community's (EEC) certification standards' Council Regulation 2092/91, passed

in 1991. The EU guideline has had a significant impact on the importation of organic apples into Europe, since importers must demonstrate that imported products meet all EEC 2092/91 standards[31].

Article 11 of the EEC 2092/91 specifies two ways for an importer to comply with the EU regulations. First, the EU can approve a country's certification system for 'third-country status', which provides complete 'equivalency'—a technical term referring to the absolute acceptance of products certified by another organization—between all EU member states and the importing country[1,33]. However, this process is arduous, and to date only seven countries (Argentina, Australia, Czech Republic, Hungary, Israel, New Zealand and Switzerland) have third-country status[35]. The second, and more frequently used method allows each member state to grant 'importer derogation', whereby the member state evaluates and approves an importing country's inspection/certification body or an individual product[1,31]. This is done on a case-by-case basis for each product or certifier, in contrast to the blanket acceptance that third-country certification grants.

Two critical pieces of information need to accompany every shipment that enters the EU from the US. First, the organic certifier must complete the European Community Certificate of Inspection form (Commission Regulation [EC] 1788/2001)[36], which ensures that the fruit has passed organic certification and inspection. Secondly, all exported products, whether organic or conventional, must have a USDA-issued phytosanitary certificate. Without both of these certificates, the entire shipment may be delayed in port, which in the worst-case scenario, could result in spoilage before reaching the buyer.

International certification

As the demand for organic produce has grown, the need to centralize the definitions of 'organic' through uniform procedures and products has become apparent. Many of the EU regulations mirror the International Federation of Organic Agriculture Movements (IFOAM) certification rules, known as Basic Standards of Organic Agriculture (BSOA). IFOAM is the self-proclaimed international umbrella organization for organic agriculture, with a diverse membership of certifying agencies, marketers, retailers, processors and individual farmers. One of IFOAM's mission statements is to assist in standardizing the various certification regulations that exist around the world by accrediting organizations involved in organic certification with their BSOA[37]. For example, CCOF and the Soil Association are accredited by IFOAM, meaning that the certifying guidelines of these organizations are in compliance with the BSOA. Through a contracted accreditation agency, International Organic Accreditation Service, IFOAM also conducts certification of individual farms.

Another international standard, Codex Alimentarius: Production, Processing, Labeling and Marketing of Organically Produced Foods, was written jointly in 1999 by the United Nations Food and Agriculture Organization (FAO) and the World Health Organization (WHO)[38]. The Codex Alimentarius, Latin for 'food law', was written for the purpose of protecting the health of consumers and to ensure fair trade. Although the joint FAO/WHO committee has little in the way of enforcing power, by setting an international standard the Codex facilitates organic trade. The Codex Alimentarius was agreed upon by a majority vote of the 163 member nations and was largely based upon standards set previously by the EU and IFOAM[1]. The Codex Alimentarius allows for more consistent standards between the various certifiers that exist throughout the world. Additionally, the World Trade Organization (WTO) uses the Codex as a benchmark for its own organic foods policy and as a guide for resolving trade disputes between parties.

A third international body, the International Organization for Standardization (ISO), is a worldwide organization made up of national standardization bodies from 140 nations. The ISO sets standardization rules on many topics, such as food pesticide residues, weights and measures, and, relative to organic agriculture, certification bodies. Developed in 1996, ISO 65, General Requirements for Bodies Operating Product Certification Systems, acts as a guideline for certifiers of any product, including organic produce, but does not set any particular production standards[39]. There is no legal requirement for certifiers to comply with ISO 65, but all exporters to the EU must use an ISO 65 accredited certifying body. IFOAM, Demeter, EU Regulation 2092/91, USDA NOP, and WSDA OFP are all in compliance with ISO 65. However, the USDA's ISO 65 certification does not extend to its accredited certifiers. With only 14 USDA-accredited certifiers currently ISO 65 certified, meeting NOP requirements is not enough to market produce in the EU.

In 2004, Pacific Organic Produce was also asked to meet another set of production standards, the Euro-Retailer Produce Working Group's Good Agriculture Practices (EUREPGAP)[40]. EUREPGAP is an international farming standard that involves compliance with the following: food safety of the product (e.g., pesticide and fertilizer use), environmental management on the farm, and worker health, safety, and welfare. Many EU retailers, for example Sainsbury (London, UK), which operates 450 stores in the UK, demand that all suppliers, whether organic or conventional, obtain EUREPGAP certification. Additionally, most UK retailers, as well as some US supermarkets, now demand accountability in ethical labor practices in addition to organic traceability.

Organic trade between the US and EU

Currently, there is no equivalency established between the USDA and the EU. However, three EU member states (UK, Spain and Denmark) do have USDA equivalency, meaning that the USDA has determined that these countries'

Table 3. Allowable practices and materials that impact organic apple orchard production under the USDA National Organic Program (NOP) and European Economic Commission (EEC) Regulation 2092/91[44].

Practice/material	Allowable under USDA NOP	Allowable under EEC 2092/91
Bonemeal (degelatinized)	No	Yes
Buffer zone	Required	Not required
Composted animal excrements, including poultry manure and composted farmyard manure	Yes	Yes
Elemental sulfur	Yes	Yes
Extract (aqueous solution) from *Nicotiana tabacum*	No	Yes
Fishmeal and bloodmeal	Yes	Yes
Herbicides, soap-based	Yes	No
Lime sulfur	Yes	Yes
Liquid fish products	Yes	No
Microorganisms (bacteria, viruses and fungi). e.g., *Bacillus thuringiensis*, granulosis virus, etc.	Yes	Yes
Oil, horticultural	Yes	Yes
Plant oils (e.g., mint oil, pine oil, caraway oil)	No	Yes
Plastic, newspaper and recycled paper mulches	Yes, without glossy or colored inks	No
Pyrethroids (only deltamethrin and lambdacyhalothrin)	No	Yes
Seaweed and seaweed extracts	Yes	Yes
Sodium hypochlorite (liquid bleach)	Yes	No
Sodium nitrate (Chilean nitrate)	Yes, up to 20% of total nitrogen input	No
Transition period	3 years	2 years

'conformity assessment programs [are] sufficient to ensure conformity to the technical standards' of the NOP[41]. Canada, Israel and New Zealand are also approved under this category, which eases imports of goods from these countries into the US, but does not specify a bi-lateral equivalency[41]. The USDA has also recently approved full equivalency with the Japanese Agricultural Standard of Organic Agricultural Products, allowing for bi-lateral acceptance of organic labels[41]. Some accreditation is occurring between EU and individual US certifiers. For example, the WSDA OFP has EU organic certification equivalency or 'importer derogation' with the Department for Environment, Food, and Rural Affairs (DEFRA) in the UK[42]. The WSDA OFP is also in the process of becoming certified by IFOAM[42]. These agreements allow certifiers, in this case the WSDA, to provide growers with multiple certifications and thus greatly improve the ease of export to the EU.

The sheer number of certifying bodies has made it challenging for those involved in the industry to keep up to date with the required production and processing standards. Since it is often specific commercial materials used in production that prevent sales of organic produce, differences in allowable materials between US and foreign guidelines must be determined for each crop and each country where organic produce is exported. Allowable material use is perhaps the most difficult information with which to keep abreast, since certifiers in both the EU and the USDA are constantly reviewing, certifying and decertifying allowable materials. For the NOP, all synthetic materials are prohibited, unless explicitly allowed; and all nonsynthetic materials are allowed, unless explicitly prohibited. The National Organic Standards Board (NOSB) scientifically reviews materials, under the guidance of Technical Advisory Panels consisting of scientists, policy makers and industry leaders. The EU code must explicitly list allowable materials, which are petitioned for by member states.

The Organic Materials Review Institute (OMRI) is an important resource for US organic growers, as it maintains a materials list that is compliant with the NOP. 'OMRI is a ... nonprofit organization created to benefit the organic community and the general public. Its primary mission is to publish and disseminate generic and specific (brand name) lists of materials allowed and prohibited for use in the production, processing, and handling of organic food and fiber'[43]. The EU maintains its own materials list under Council Regulation (EEC) 2092/91. The Organic Trade Association (OTA) has published an exhaustive comparison of materials between the USDA NOP and EEC 2092/91[44]. For example, antibiotics, such as streptomycin, and sodium nitrate (i.e., Chilean nitrate), allowable for up to 20% of the total nitrogen input for a farm under the NOP, are completely prohibited for growers who wish to market to the EU. On the other hand, the EU allows degelatinized bonemeal and nicotine extracts, which are prohibited under the NOP (Table 3).

While it is the responsibility of the grower to stay abreast of all relevant certification standards, and therefore allowable materials, growers rely heavily on their certifiers and marketers for current and pertinent information. Yet despite all of this information, there is still considerable confusion over allowable inputs, leaving growers and certifiers with the time-consuming task of keeping abreast

of the allowable materials within each export market. Many European buyers have requested Pacific Organic Produce to produce a complete list of orchard management practices and materials before allowing a sale. When exporting to the UK, for example, Pacific Organic Produce has also had to supply detailed records from every grower they do business with, including their production tonnage, date of first certification, and their most recent farm inspection report. This information is passed on to the European certifier to verify that the practices meet European standards. Occasionally, Pacific Organic Produce has even been asked to supply records of materials applied by their growers in past growing seasons to gain approval from a foreign certifier.

Discussion

As returns on organic apples decline, the profit margin for organic orchard operations in Washington State will continue to narrow. With industry leaders from the conventional market expanding their organic holdings and providing buyers with convenience and consistency, smaller marketing firms will likely find it difficult to compete and may be usurped by the larger operations with more efficient economies of scale. Additionally, organic growers who do not use the latest available technologies, such as organically certified pesticides, labor-saving weed-control tools and chemical thinning, might have a difficult time maintaining an economically sustainable enterprise.

Competition in organic fruit production will be increasing from France, Germany, Italy and Israel in the northern hemisphere, and Argentina, Chile, New Zealand and Australia in the southern hemisphere. Additionally, the ten new member states to the EU may start supplying organic apples in high volume to other EU member states, without the barriers to trade that US growers encounter. As in the conventional apple market, China may potentially become a significant player of organic apples, but as of now Chinese organic fruit has not been regularly seen in the EU marketplace. These are all examples of the potential for market saturation and, as a result, may decrease profitability.

Further complicating the situation, an organic grower cannot automatically be assured of finding a buyer, since, like the conventional market, the organic market is very competitive and subject to extreme price swings. The organic apple market demands less volume than the conventional, and is more easily flooded with a surplus supply, driving down prices. If this happens, it is possible that specific cultivars, sizes and color grades of organic apples would receive higher prices in the conventional market. This may also occur when there is a shortage of conventional apples in the marketplace. Nevertheless, a cultivar marketed through the right channels, at the right time, will likely receive adequate price premiums.

For Pacific Organic Produce, newer cultivars, such as 'Pink Lady', command a high price premium since availability is currently limited. Pacific Organic Produce sells the greatest volume of 'Braeburn', 'Gala', and 'Fuji' apples in small fruit sizes (carton counts of 113 to 138 fruit per 42-pound carton) to Europe. Apples are often re-graded according to each country's size standards and transferred into bags or punnets by the importing buyer before retail sale. For example, 'Gala' apples are sold as small as 198 fruit per carton in the UK, where they are then repackaged into plastic bags. However, larger retailers, such as the Wal-Mart subsidiary, ASDA (Leeds, UK), the UK's second largest grocery store chain, do make special demands, such as requiring fruit to be bagged before shipping. The potential to sell smaller fruit to the EU is an excellent complement to the domestic market, which tends to command higher prices for larger fruit. To enhance profitability, Washington State's organic apple growers and marketers need to target a wider range of consumers by exploring new markets, increasing sales to existing EU markets and by developing sales strategies that satisfy buyers. Pac Organic Fruit, for example, created small fruit packs that target children and home-delivery businesses in the EU. They have also developed biodegradable packaging and a labeling scheme that promotes small family farmers by packing each grower's fruit in boxes identifying the individual farms.

Despite the market opportunities for organic apples in the EU, growers must contend with an enormous bureaucracy. A US organic apple grower may have to deal with the standards of as many as six certifying bodies, and their particular codes for acceptable materials, record keeping and general farm management. Washington State growers and marketers selling to the UK, for example, must meet both EU Regulation 2092/91 and DEFRA standards, but depending upon the buyer, they may also need to meet the Soil Association or IFOAM BSOA certification. In the US, growers may have to work with the NOP, a third-party USDA-accredited certifier such as CCOF or Quality Assurance International, or state certifiers, such as the WSDA OFP. For Pacific Organic Produce, it can take between 3 and 6 months to get all the paperwork in order and make the transportation arrangements when developing new markets or adding new buyers to existing markets. Additionally, the number of certifiers involved in the international organic apple trade has been steadily growing. Buyers may desire to have one certification standard met in one year, but change the requirements the next. Clearly, very thorough record keeping will help facilitate the export process.

In the future, uniform international codes will help ease the regulatory burden on organic growers and marketers. IFOAM has standards that are most often reproduced by other certifying bodies, largely due to this organization's mission of unifying international standards. The FAO/WHO's Codex Alimentarius organic regulations are relatively new, but in the future they may help to further

multilateral trade in organic produce by setting international standards that are used in the event of trade disputes. The future of certification will likely be based on guidelines from IFOAM, the Codex Alimentarius and compliance with ISO 65. At present, the most important advance that will increase acceptability for importing US organic fruit into Europe will be equivalency between the NOP and EU Regulation 2092/91.

Another aspect of the internationalization of the organic fruit market that we must question is whether it is sustainable to ship organic apples halfway around the globe to meet European demand. With the current political instability in oil-producing regions and rising concerns about the effects of fossil fuels on global warming, we must remember that most organic apples are shipped to Europe by diesel-powered freightliners. Assessments of food-supply chains have shown that importing apples into the EU from overseas requires more than twice the energy of delivering a European grown apple to the same European supermarket[45,46]. The additional energy cost is almost entirely contributed by transportation. At some point these concerns will likely be included in organic certification schemes, as 'buy-local' labeling campaigns already exist in the marketplace.

Conclusions

Although organic agriculture has been thought of as a grassroots and perhaps ideological movement, the regulation and certification procedures for organic foods have become highly institutionalized. While certification programs help define organic agriculture and thus allow for easier sales, the sheer number of certification programs involved in international organic trade limits the ease of global marketing. In an attempt to mitigate trade barriers, the USDA and the EU have unified standards within their borders, but these two bodies have so far not agreed to accept each other's organic codes unequivocally. This puts the burden of proof upon US organic apple growers and brokers to illustrate that they not only meet USDA standards, but also EU standards. To complicate matters, European buyers may ask that US growers meet other organic standards, such as IFOAM or the Soil Association, and in some cases growers are required to meet additional standards, such as EUREPGAP. None the less, organic apple production has soared in Washington State, while the premiums that growers had relied upon have shrunk. Coupled with continued EU demand for organic fruit, it is clear that the EU will remain a profitable market for Washington State's organic apple growers.

The future will see continued growth in the organic market, but most likely at a slower rate, at least in the near term, than has occurred thus far. Many growers who think organic certification is a good business move but lack the commitment to its core values may find the additional challenges that organic systems present difficult, and are therefore unlikely to remain in the organic market long. Nevertheless, food safety scares, public distrust of genetically modified crops and possible health benefits from eating organic produce will all help to increase organic food sales. In the end, as organic food continues to expand its market share, farmers will have more management options and economic opportunities, consumers will have more choices in the marketplace and society will likely accrue greater environmental benefits.

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Chemical changes under aerobic composting and nutrient supplying potential of banana residue compost

Venecio U. Ultra Jr[1,*†], Danilo M. Mendoza[2], and Angelina M. Briones[2]

[1]University of Eastern Philippines, Catarman, Northern Samar, Philippines.
[2]Department of Soil Science, University of the Philippines Los Banos, College, Laguna, Philippines.
*Corresponding author: ultra@cc.kochi-u.ac.jp

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Abstract

In anticipation of the Philippines being a major producer of organic bananas, this study was conducted to provide a quantitative basis for certain practices in organic farming. The nutrient supplying capacity of banana residues in combination with leguminous materials and chicken manure was investigated in composting studies. Changes in the chemical composition of ten formulations of banana residue-based compost involving leguminous plants (*Sesbania rostrata, Flemingia macrophylla, Arachis hypogea*) and chicken manure were analyzed periodically during a composting period of 16 weeks. Results showed that combinations of banana residues (BnR) and chicken manure or leguminous plants were highly decomposed compared to untreated BnR. The use of leguminous plants and/or chicken manure enhanced the composting process significantly compared to the effect of Bioquick. The compost piles were characterized by increases in pH, total N and total P, and decreases in total K, total carbon and C/N ratio with time. Notably, BnR + chicken manure attained a C/N ratio of 15 at 4 weeks, while the BnR + leguminous materials reached such a low C/N ratio at 8–16 weeks. An incubation study was conducted under greenhouse conditions for 24 weeks. It was designed to follow the dynamics of nitrogen (N), phosphorus (P) and potassium (K) availability in two clay soils (Antipolo and Lipa) amended with five compost formulations (BnR alone, BnR + *Sesbania* prunings, BnR + *Flemingia* prunings, BnR + peanut stover and BnR + chicken manure) and with uncomposted banana residue at an application rate of 20 Mg ha^{-1}. Results showed that net N mineralization occurred in soils amended with BnR + chicken manure and BnR + leguminous materials, which had C/N ratios ranging from 12 to 16. Net N immobilization during the earlier period of incubation was observed in uncomposted and composted banana residues with a C/N ratio of 68 and 24, respectively. Significantly higher net P mineralization was obtained only in soils amended with BnR + chicken manure. An abrupt increase in exchangeable K was observed in all treatments 2 weeks after the incorporation of organic residues. Higher available K in pure BnR treatments (uncomposted or composted) exhibits the inherently high K content of banana residues.

Key words: aerobic composting, *Arachis hypogaea*, banana residue, chemical characteristics, *Flemingia macrophylla*, organic farming, *Sesbania rostrata*, NPK availability

Introduction

Global awareness of the need to use renewable resources has revived our interest in organic agriculture. Existing conventional practices employ the use of farm inputs manufactured from high-energy and resource-consuming processes that, more often than not, lead to the depletion of non-renewable energy sources and degradation of natural environment. Currently, modern agricultural production systems have high dependence on synthetic fertilizers and other agrochemicals to attain high yield levels.

One alternative to conventional agriculture is the adoption of organic farming governed by the principles of natural ecosystems, and promoted by natural ecological cycles and sound management practices. The basic idea of organic agriculture focuses on the establishment of farm systems that are practically sustainable, ecologically stable and economically viable in the long term[1]. This can be

†Current address: Department of Plant Nutrition, Faculty of Agriculture, Kochi University, Nankoku City, Kochi, 783-8502 Japan.

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achieved through the ecological integration of diverse farm components and indigenous farming systems that are not dependent on synthetic chemical inputs. In addition, organic farming is considered as an interdependent system. Its long-term productivity is realized by diverse combinations of crop production and animal husbandry through appropriate crop rotations, green manuring, recycling of farm residues and other practices promoting healthy and biologically active soil[2]. In essence, organic agriculture is geared towards sustainability and productivity, with little unfavorable impact on the environment and society.

Such ecological benefits are boosted further by high market growth. Organic agriculture is entering the new millennium with worldwide booming organic markets; e.g., 25–30% growth annually[3]. In the Philippines, some companies in the banana industry have started to venture into organic production systems. They not only have an eye on the high demand for organic bananas in foreign markets, but plantation owners also want a shift into organic farming to avoid prevalent problems in the conventional system. In addition, non-governmental organizations (NGO) have started to organize some farming communities, composed of small-holder farmers, to venture into organic production systems[4]. They are also aware that there are standards of organic production that should be complied with. The standards include principles that cover a broad range of objectives (economic, ecological and social)[1,5]. But organic farmers recognize the fact that a key to sustainable production is the improvement of soil fertility and maintenance of soil productivity.

Successful conversion of conventional commercial banana plantations to organic farms needs more efficient residue utilization schemes, to meet the nutrient demand of the banana plant and increase utilization efficiency[6]. With regard to soil fertility build-up and sustainability, experience from fully established organic farms showed that the farming systems[4] should include diverse plant and animal components capable of compensating for nutrient removal brought about by the export of nutrients in the harvested plant parts. Apart from the residues of the main crop, incorporation of nutrient builders, such as leguminous plants and other plant species with high nutrient value, and animal manure are recommended as effective measures in enhancing soil fertility.

A commercial banana plantation can generate a considerable amount of banana residue, consisting of leaves, pseudostem, inflorescence, pruned sucker, bunch-stalk and fruits rejected immediately in the field and from the packing house. About 76% of plant parts are left as crop residue after harvest. The crop residue per hectare per year could amount to around 7.3 Mg dry matter[6]. The chemical composition of these plant parts ranged from 0.8 to 1.45% nitrogen (N), 0.1–0.46% phosphorus (P), 5.73–17.51% potassium (K), 2.33% calcium (Ca) and 0.39% magnesium (Mg) on a dry weight basis[7]. Most notable is the high concentration of potassium in pseudostem and stalk. The C/N ratios of the different plant parts range from 17 for rachis to 53 in leaves.

Very few studies have been conducted to explore the potential of banana residue as green manure or as compost. One common method in handling banana waste is by fermentative composting, termed 'Bokashi'[8,9], but most commercial plantations leave the residues in the field and do not seriously consider them as a source of nutrients[6]. In converting conventional into organic banana farms, one should carefully consider the huge amount of banana residue as a source of plant nutrients. One popular and effective practice is composting. The process of composting will not only render the potentially hazardous organic materials harmless but, through the exothermic and bio-oxidative reactions of composting, the process will also convert organic material into a more stable form that, upon application, will not degrade the soil[10]. Otherwise, further decomposition will continue at the expense of soil nitrogen and other nutrients needed for microbial metabolism.

Although several studies have been conducted about the composting process of crop residues, very few have been conducted on banana residue in combination with leguminous materials and chicken manure. This study was conducted to augment meager research on organic agriculture in the Philippines, but it cannot strictly adhere to requirements in the standards that residues for recycling must also come from organic farms. Nevertheless, the focus of this study is on chemical characterization of banana residue (with and without other organic residues) during the composting process, and on the dynamics of available N, P and K in compost-amended soils. Specifically, the objectives of this study were: (1) to determine changes in the chemical composition of banana residue with various combinations of legume residues, chicken manure and composting inoculants over time of decomposition; and (2) to determine the amounts of available N, P and K released from soil samples amended with various preparations of banana-residue composts.

Materials and Methods

Experiment 1: Composting banana residue in combination with other organic materials

Treatment composition and description. Banana residue (BnR) of the cultivar Cavendish, a commonly grown variety in commercial plantations, together with *Flemingia macrophylla*, *Sesbania rostrata* and *Arachis hypogaea* and chicken manure, were utilized in the experiments. Although appropriate materials for composting should come from sources conforming to the standards of organic farming, only the leguminous materials have been grown under the conditions of an organic farm. Chicken manure came from a conventional poultry farm. The possible contribution of a composting inoculum on decomposition and nutrient content was evaluated by subjecting the mixtures to inoculation. Bioquick, a fungi

Table 1. Chemical composition of the raw materials used in the composting experiment.

Organic material	Total N	Total C	Total P	Total K	C/N ratio
	(%) dry weight				
Banana residues	0.70	47.72	0.13	7.71	68
Sesbania prunings	2.87	50.41	0.17	1.64	18
Flemingia prunings	2.73	54.00	0.13	1.49	20
Peanut stover	2.52	50.684	0.09	0.75	20
Chicken manure	3.36	37.59	1.45	4.67	12

composting inoculant from the National Institute of Molecular Biology and Biotechnology (BIOTECH) of the University of Philippines Los Banos (UPLB), was utilized. The initial chemical composition of the organic materials prior to composting is presented in Table 1. The treatment combinations used in this experiment are summarized in Table 2. The experiment was laid out following a complete randomized design with three replicates.

Procedure for compost preparation. Composting was carried out using containers made up of encircled chicken wires with 63.5 cm diameter and 30.48 cm height. A total of 30 containers were constructed to accommodate the 10 treatment combinations having three replications. Compost preparations followed the steps outlined by Cosico (1995)[10]. Briefly, the plant materials were chopped and air-dried prior to mixing, based on the proportions given in Table 2. The materials were then placed inside the wire containers. Microbial inoculation was carried out following the recommended application procedure for the product. The files were moistened thoroughly during the incubation period, using a fine mist spray in order to prevent the water from leaking outside the set-up. Watering was carried out regularly to avoid drying, and the set-up was covered with polyethylene plastic sheets in order to prevent excessive evaporation or leaching and disturbance from extreme weather conditions. Incubation was carried out on a concrete surface covered with polyethylene sheets. Manual mixing was done every 2 weeks to distribute the undecomposed materials uniformly and aerate the system. The set-up was observed and evaluated up to 16 weeks or until the compost was judged mature. Compost maturity was assessed based on the following characteristics of mature compost: no foul odor, dark brown in color, crumb-like texture, soil-like appearance, pH of 8–9, and a C/N ratio between 10 and 12. Compost file temperature and oxygen evolution were not monitored while the mean ambient daily temperature during the composting process ranged from 20–26 (minimum) to 29–35°C (maximum).

Sampling procedure and analysis. Samples were collected from each treatment at 4-week intervals from the start of the composting process until 16 weeks. Bulk samples from the center of the compost pile were collected and mixed. A subsample for analysis was taken and oven dried at 70°C for 3 days prior to analysis. The rest of the bulk samples were returned to the pile.

The chemical characterization of compost during the whole composting duration was based on the standard procedures of analysis for soil, plant tissues, water and fertilizer that were compiled by the Philippine Council for Agricultural Resources Research and Development (PCARRD)[11]. Briefly, total N was measured by Kjeldahl digestion and distillation, using sulfuric acid and a salt mixture of potassium sulfate and copper chloride (1000:32, w:w), followed by steam distillation using boric acid as receiver and standard acid titration in the presence of an indicator. Total carbon was analyzed by loss in ignition at 430°C for 24 h. Total P and K were analyzed by dry ashing

Table 2. Treatment composition, NPK concentrations and carbon contents of different compost preparations before and after aerobic composting of Experiment 1.

Treatments	Nitrogen		Phosphorus		Potassium		Carbon	
	Initial	Final	Initial	Final	Initial	Final	Initial	Final
	% DW							
T1: banana residue (BnR) alone	0.70 f	1.36 h	0.21 d	0.33 e	7.71 f	6.72 b	47.72 ab	35.36 abc
T2: BnR + Bioquick (BQ)	0.71 f	1.45 g	0.22 d	0.36 e	7.69 f	6.96 a	47.65 ab	34.80 abc
T3: BnR + *Sesbania* + BQ (1:1, w:w)	1.80 c	2.32 f	0.19 de	0.34 e	4.67 b	4.29 d	49.56 a	37.12 a
T4: BnR + *Flemingia* + BQ (1:1, w:w)	1.72 d	2.42 d	0.17 de	0.27 f	4.59 b	3.99 e	50.55 a	36.30 ab
T5: BnR + peanut + BQ (1:1, w:w)	1.61 e	2.56 b	0.14 e	0.25 f	4.20 c	4.37 c	48.75 ab	35.84 ab
T6: BnR + chicken manure (CM) + BQ (1:1, w:w)	2.03 a	2.58 b	0.83 a	0.80 b	5.69 a	4.03 e	42.35 c	30.96 c
T7: BnR + *Sesbania* + CM (2:1:1, w:w:w)	1.91 b	2.36 e	0.46 c	0.74 c	3.40 d	2.73 g	46.10 b	30.68 cd
T8: BnR + *Flemingia* + CM (2:1:1, w:w:w)	1.87 bc	2.75 a	0.55 b	0.59 d	3.02 e	2.91 f	49.89 ab	35.75 abc
T9: BnR + peanut + CM (2:1:1, w:w:w)	1.82 a	2.48 c	0.54 b	0.57 d	3.00 e	2.86 f	46.20 b	29.76 d
T10: BnR + chicken manure (1:1, w:w)	2.10	2.49 c	0.59 b	0.87 a	3.34 d	2.77 g	42.50 c	32.37 bc

Means within the same column followed by the same letter(s) are not significantly different from each other at the 5% level, based on least significant differences (LSD).

in a muffle furnace (550°C) for 4 h, followed by acid digestion using HCl. The digests were analyzed by atomic adsorption spectrophotometry (Shimadsu AA660, Kyoto, Japan) for K, while P was measured by colorometry, using the vanado-molybdophosphoric acid method and a spectrometer at 470 nm. Changes in pH (1:5 w/v water, electrode) and C/N ratio were monitored during the composting process, with particular consideration of C/N ratio reduction as an index for the degree of decomposition. All the data obtained were subjected to analysis of variance, with consideration of the interaction between treatment and time of sampling. Separation of treatment means was based on least significance differences at the 5% level.

Experiment 2: Nutrient availability in compost-amended soils

Soil characterization. Surface soil (0–20 cm depth) samples, representative of Antipolo clay (Antipolo City, Philippines) and Lipa clay (Lipa City, Batangas, Philippines), were collected from fields in which bananas were grown. Bulk soil samples were air-dried and sieved through a 2 mm-diameter screen wire to remove undecomposed organic material. The physical and chemical properties of the two soils are given in Table 3 . Antipolo is an extremely acid and a heavy clay soil; it is low in organic matter, total N, available P and exchangeable K. The moderately acidic Lipa clay has nutrient levels which are relatively higher than those in the Antipolo clay.

A total of 42 pots (21 pots for each type of soil) containing 10 kg soil were prepared and stored prior to the application of organic materials. Mature composts derived from Experiment 1, and raw banana residues were used as amendments for the soil incubation study (Experiment 2). The materials were air-dried and ground to pass a 60-mesh sieve. Representative samples from these materials were taken and analyzed for total C, N, P and K, as described in Experiment 1.

Treatment composition and incubation set-up. Seven treatments (see Table 6) were imposed on each of the two soils. The treatments were laid out following a split-plot design, with soil type as the main plot and organic amendment assigned as the subplot. Treatment application was done by incorporating 100 g dry weight of the previously prepared material into 10 kg soil, or an equivalent rate of 20 Mg ha^{-1}.

Predetermined amounts of the different materials were mixed thoroughly with the prepared soil in the pots. Distilled water was added to attain a moisture content approximately equal to 70% of the field capacity. The amount of water needed was applied using a weighing method. Each pot was weighed every 3 days and the weight loss was replaced with distilled water to keep the moisture content constant throughout the incubation period. Soil available N (NH_4-N and NO_3-N), available P, and exchangeable K were measured from 2 to 24 weeks. For each treatment, the incubation was carried out in triplicate.

Sampling and laboratory analysis. Soil samples from the incubation set-up were collected for laboratory analyses at predetermined time intervals. Five subsamples from each pot were taken and mixed thoroughly to create a representative sample. Sampling was carried out using a small core sampler. The soil collected in each pot was just enough to provide the needed amount for analysis. All samples were air-dried and sieved to pass through 2 mm mesh. Available N/mineral N was determined by 2 *M* KCl extraction followed by closed system, steam distillation; available P by 0.1 *N* HCl–0.03 *N* ammonium fluoride extraction (Bray P2); while exchangeable K was determined by 1 *N* ammonium acetate (pH 7) extraction followed by AAS[11].

Results and Discussion

Experiment 1: Chemical changes of banana residue under aerobic composting

Initially, banana residue had a low N content as compared to the leguminous plant residues and chicken manure. Total N content of the legumes gave a narrow range (2.52–2.87%) in the order: *Sesbania* prunings > *Flemingia* prunings > peanut stover. Chicken manure had the highest total N and the lowest total C, hence the lowest C/N ratio. In terms of nutrient composition, chicken manure had higher P and K content compared with the plant residues, except for banana which contained the highest K. The C/N ratio of the raw materials varied from as low as 11 for chicken manure to as high as 68 for pure banana residue; the leguminous materials had a relatively low C/N ratio (18–20). Chemical changes of banana-residue-based compost were monitored through pH, total nitrogen, phosphorus and potassium, total carbon and the C/N ratio of the compost pile during the decomposition process.

Compost-pile pH. Table 4 shows that, over time, the pH of the different compost preparations changed from slightly acidic to alkaline. The initial pH of the material ranged from 6.25 to 6.51, values that are typically similar to the pH of plant sap[12]. Significant pH reduction was observed at 4 weeks of incubation in all treatments. However, treatments involving the combination of banana residue with either leguminous materials or chicken manure had higher magnitudes of pH reduction as compared with those treatments containing banana residue alone (T1 and T2). Acidification in T1 and T2 ranged from 0.13 to 0.16 pH units, while the remaining treatments acidified more or less by 1 pH unit. Continuous acidification was observed in the two banana residue treatments (T1 and T2) until 16 weeks of composting. In contrast, all legume treatments (BnR + legumes) showed a slight increase in pH at 8 weeks. A significant pH increase (>1) was observed on the chicken manure treatment (BnR + CM) at 8 weeks. By the 12th week, pH increase in these treatments (BnR + legumes or chicken manure) was large enough to reach alkaline levels (7.7–8.7) and generally leveled off at 12–16 weeks.

Table 3. Some physical and chemical properties of soils used in the experiment.

Soil property	Antipolo clay	Lipa clay
Sand (%)	1.1	12.8
Silt (%)	15.0	38.1
Clay (%)	83.9	49.0
Moisture content at FC (g water per100 g soil)	36.20	30.67
Organic matter (%)	0.69	2.73
Total nitrogen (%)	0.4	1.15
NH_4-N + NO_3-N (mg N kg^{-1})	33.41	32.33
Available P, Bray P2 (mg P kg^{-1})	1.68	23.16
Exchangeable K (cmol+ kg^{-1})	0.11	1.75
CEC (cmol+ kg^{-1})	21.1	34.1
pH	4.43	5.83

FC, field capacity; CEC, cation exchange capacity.

Table 4. Changes in pH of different compost preparations during incubation.[1]

	Incubation period (weeks)				
Treatment	**0**	**4**	**8**	**12**	**16**
T1	6.23 a	6.10 b	6.12 b	5.58 c	5.32 d
T2	6.24 a	6.08 b	6.05 b	5.62 c	5.49 d
T3	6.38 b	5.25 d	5.38 c	8.12 a	8.12 a
T4	6.42 c	5.32 e	5.42 d	8.72 a	8.18 b
T5	6.51 c	5.42 e	5.63 d	8.01 b	8.21 a
T6	6.32 c	5.22 d	6.75 b	8.20 a	8.20 a
T7	6.46 b	5.32 c	5.42 c	8.32 a	8.26 a
T8	6.48 c	5.38 d	5.39 d	7.65 b	8.38 c
T9	6.62 c	5.43 d	5.72 e	7.82 b	8.69 a
T10	6.38 c	5.39 d	6.62 b	8.56 a	8.52 b

[1] Means within the same treatment (row) followed by the same letter(s) are not significantly different from each other at 5% level, based on least significant differences (LSD).

Table 5. Changes of the C/N ratio of the different compost formulations at different sampling periods.[1]

	Incubation period (weeks)				
Treatments	**Initial**	**4**	**8**	**12**	**16**
T1	68 a	48 b	37 d	23 o	26 kl
T2	67 a	38 c	36 e	28 h	24 no
T3	27 hi	25 lm	20 qr	20 qr	16 v
T4	29 g	26 jk	22 p	19 s	16 v
T5	30 f	19 s	18 t	17 u	14 x
T6	21 q	21 q	22 p	17 u	12 z
T7	24 mn	21 q	20 qr	22 p	13 xy
T8	27 ij	18 t	15 vw	17 u	13 xy
T9	25 m	22 p	15 vw	13 xy	12 z
T10	20 qr	15 vw	12 z	12 z	13 xy

[1] Means followed by the same letter(s) are not significantly different at 5% level based on least significant differences (LSD).

The reduction in pH during the early stage of composting is due to accumulation of organic acids released during the decomposition process[13]. This is further enhanced by the solubilization of carbon dioxide at high moisture content. Increased pH at a later stage indicates compost maturity brought about by either lowering of microbial activity and carbon dioxide evolution, or accumulation of basic substances such as ammonia. The extent of pH change among treatments indicates the degree and stage of decomposition of the compost pile and the rate at which the reaction is taking place[14,15]. A greater pH reduction in treatments containing the combinations of banana residue, legumes sources and chicken manure at the fourth week of composting, compared to the banana residue alone, indicates a faster rate of decomposition taking place. The pH of the banana residue compost pile (T1 and T2) continuously and gradually declined until the sixteenth week of composting, unlike the other treatments in which pH initially turned acidic at 4 weeks then became alkaline at 12 weeks. This result indicates that banana residue (inoculated and uninoculated) did not reach maturity, even at 16 weeks of composting, while all other treatments rendered the composts mature at week 12 of the composting period.

NPK and carbon content. The NPK and carbon concentration of different banana residue-based compost formulations before and after the 16-week composting process are presented in Table 2. The nitrogen concentration of pure banana residue (T1 and T2) increased significantly during the 16-week composting period—the N content practically doubled the initial concentration. In all other treatments, total N of each compost at 16 weeks was significantly higher than the initial concentration. However, a consistent increase with time was not observed in all these treatments during the 16 weeks of composting. Some treatments showed inconsistent trends before the sixteenth week. A slight reduction in total N with time can be attributed to volatilization of NH_3 and/or leaching from the decomposing materials. None the less, the final N concentration showed that treatments containing chicken manure and/or leguminous materials have higher nitrogen content than pure banana residue compost.

Total P concentration of the compost piles changed variably during the 16-week composting period. At final sampling, all treatments expect T6 had higher P compared to initial content (Table 2). This general increase in P content was brought about by the decrease in the carbon content of the material, resulting in an increase in the concentration of P relative to the total proportion of the materials/components. With respect to the P-supplying potential of the different compost formulations, the results revealed that inclusion of 25% chicken manure would increase the total P content of the banana residue compost. Chicken manure could increase the total P content of the product by more than 70% as compared with compost formulations containing banana residue and leguminous plant material alone.

Table 6. Treatment composition and nitrogen, phosphorus and potassium contents, and C/N and C/P ratios of compost amendments used in the incubation experiment at 20 Mg ha^{-1}.

	N		P		K			
Treatment	**%**	**kg/ha**	**%**	**kg/ha**	**%**	**kg/ha**	**C/N**	**C/P**
T1: soil alone	–	–	–	–	–	–	–	–
T2: soil + air-dried banana trash (BnT)	0.7	140	0.21	42	7.71	1542	68	227
T3: soil + BnT compost	1.45	290	0.36	72	6.69	1338	24	128
T4: soil + BnT and *Sesbania* compost	2.32	464	0.34	68	4.29	858	16	142
T5: soil + BnT and *Flemingia* compost	2.42	484	0.27	54	3.99	798	16	186
T6: soil + BnT and peanut compost	2.56	512	0.25	50	4.37	874	14	193
T7: soil + BnT and chicken manure compost	2.58	516	0.80	160	4.03	806	12	51

Unlike P, the K in plant material is not usually bound to organic compounds, thus existing in its free ionic form[16], and usually declining upon decomposition. In the experiment, a significant reduction in K content was observed in all treatments during the whole 16 weeks of composting (Table 2). An average reduction of about 29% was observed. The final K content of the different compost formulations differed significantly from each other. Compost made from pure banana residues alone (without Bioquick inoculation) had the highest K content. This was followed by T2, T5, T3, T6 and T4 in decreasing order. Much lower K content was observed on T8, T9, T10 and T7. The inherently high K content of banana residue renders it a good material to be mixed with residues containing high N and high P.

The C content of the decomposing materials decreased during the composting process (Table 2). Carbon content of compost piles containing chicken manure were generally lower than those treatments inoculated with Bioquick in combination with leguminous materials alone. An average reduction of 28% from the initial carbon content was observed for the treatments at final sampling. Carbon was lost as carbon dioxide during the decomposition process. These results show that a higher C loss throughout the composting period occurred in treatments having an initially high nitrogen content compared to those with lower N content (T1 and T2). This is consistent with common observations that organic residues with high initial nitrogen content favor a faster rate of decomposition[13,15].

C/N ratio. Probably the most important aspect of successful composting is the reduction of C/N ratio and its relationship to the rate of organic matter decomposition. Microorganisms require a carbon source for growth as well as a source of nitrogen for protein synthesis; hence changes in the C/N ratio of organic materials represent the overall biochemical reactions of the system. In composting, the maturity of composts is generally gauged by the C/N ratio of the product. According to Inoko[14] a C/N ratio of 10–12 for finished compost is usually the lower limit at which the robbing of soil nitrogen will not take place. However, it has been pointed out that values over this are acceptable if the excess C is in a relatively undegradable form[14,15].

Changes in the C/N ratio of the different compost formulations (Table 5) were observed to decrease significantly over the sampling period. At the fourth week of sampling, a significant reduction of the C/N ratio from the initial value was observed in all treatments except T6, but by the eighth to twelfth week of sampling, all treatments had a significant reduction from the initial C/N ratio. However, this significant reduction in the C/N ratio did not guarantee that the compost could be considered as mature compost. As a matter of fact, treatments containing banana residue alone, with or without Bioquick (T1 and T2), showed a significant narrowing of the C/N ratio during the entire composting process, but failed to qualify as a mature compost. All compost piles containing chicken manure and/or leguminous materials had a C/N ratio approximately within the range of mature compost (i.e., 10–15). Based on C/N ratios alone, this result suggests that for 16 weeks of composting banana residue-based formulations, incorporation of leguminous materials and chicken manure took the compost file to maturity. Moreover, only the 1:1 combination of banana residue and chicken manure (T10) attained a C/N ratio of 15 by the fourth week. The combinations of BnR + *Flemingia* + CM (T8) and BnR + peanut stover + CM at 2:1:1 (T9) reached a similar C/N ratio by the eighth week. These results show that, on the basis of a C/N ratio of 15, a four-week composting period for a 1:1 mixture of banana residue and chicken manure is sufficient. Increasing the proportion of banana residue in the mixture (as in the 2:1:1 treatments) means lengthening the composting period to 8 weeks.

The C/N ratio of banana residue plus inoculant at 16 weeks was not significantly different from that of uninoculated banana residue, the C/N ratio of which decreased from 68 to 26. Although the use of this compost activator in the presence of high nitrogen-containing leguminous plant materials produced compost with a C/N ratio of 15 at week 16, this effect was probably due more to the legume incorporation than the inoculant effect.

Experiment 2: NPK availability in compost-amended soils

Chemical composition of organic matter amendments. The nutrient composition (N, P and K) and C/N and C/P ratios of the organic amendments are presented in Table 6. The table includes the NPK equivalents contained in the materials at 20 Mg ha^{-1}. The total N content of the organic amendments ranged from 0.7% for treatments containing air-dried banana residue to as high as 2.58% for composted banana residue + chicken manure. The banana residue in T2 applied at 20 Mg ha^{-1} [oven dry weight (ODW) basis] had the lowest N contribution, of 140 kg ha^{-1}. This rate was almost doubled for T3, for which the total N contribution from composted banana residue alone was equivalent to 290 kg ha^{-1}. Other treatments (T4, T5, T6, and T7) had N levels three times higher than T2.

The P content of the organic amendments ranged from 0.21% to as high as 0.80%. The nutrient P addition likewise varied considerably among treatments, ranging from 42 kg P ha^{-1} for T2 to 160 kg P ha^{-1} for T7. In terms of the potassium content, a higher percentage of K was present in T2 than in the rest of the treatments. Unlike P and N, wherein T2 had the lowest N and P added to soil, the K present in this treatment was about 1542 kg K ha^{-1} and was considerably higher than in the rest of the treatments. Evidently, the compost-amended soils had varying levels of nutrient-supplying potential. Treatments 2 and 3 had lower N-supplying potential, but were high in K, while T7 was the reverse. On the other hand, the treatments receiving composted banana residue and legume combined had almost the same range of nutrient-supplying potential, intermediate to that of treatments 2 and 7.

In terms of the C/N ratio, a decreasing value was obtained from T2 until T7. The C/N ratio of all treatments ranged from 68 to as low as 12. Among the treatments, composted banana residue + chicken manure had a C/N ratio characteristic of a mature compost. However, amendments made of composted banana residue and leguminous materials had a C/N ratio low enough to be considered as ripe compost, especially as the bulk of its C content may have come from materials high in lignin and cellulose, which are relatively resistant to microbial attack[6]. Similarly, the C/P ratios of the compost varied. Values decreased in the order: T2, T6, T5, T4, T3 and T7.

Dynamics of nitrogen availability. Available soil N (NH_4-N + NO_3-N) over 24 weeks of incubation varied with sampling time. The initial concentrations of available N in the soils were 33 mg kg^{-1} for Antipolo and 32 mg kg^{-1} for Lipa (Table 3). Figure 1a shows slight fluctuations during incubation for each of the unamended soils.

The addition of 20 Mg ha^{-1} of various compost/organic residue preparations led to significant changes in the quantity of extractable ammonium and nitrate N. Figures 1b–g show the net mineralization or immobilization due the different organic amendments on nitrogen availability, and was computed by subtracting the initial amount of available N (NH_4-N + NO_3-N) from that obtained at each sampling period. Net available N ranged from negative to positive values. A positive value means net mineralization, while negative values mean net immobilization.

In Antipolo clay, treatments involving soils amended with composted BnR + chicken manure (T7) and composted BnR + peanut stover (T6) were the only amendments to give net mineralized nitrogen throughout the incubation period (Figs 1f and 1g). Other treatments have fluctuating available nitrogen as a result of either net mineralization or net immobilization. Net immobilization of available N occurred throughout almost the entire incubation period for T1 (control) and T2 (uncomposted banana residue). Immobilization of available N appeared as a natural consequence of microbial activities in an extremely acid soil[17]. The addition of uncomposted banana residue with wide C/N ratio caused a greater extent of immobilization within the first 2 weeks of incubation. In contrast, the initial immobilization in T3 (banana compost) shifted into net mineralization after the first month of incubation.

Generally, Lipa clay had a less dramatic response to organic amendments. Unlike in Antipolo clay, the application of air-dried banana residue on Lipa clay did not cause net immobilization of native available nitrogen (Fig. 1b). It was only T3 that caused net immobilization during the 4th week (Fig. 1c). All other treatments showed higher available N than the initial concentration. Similarly, the treatments containing higher amounts of nitrogen resulted in higher mineralization rates. Generally, the magnitudes of mineralized N followed: T7, T6, T4, T5, T3, T2 in decreasing order, but maximum values were obtained at different incubation stages. Highest mineralization in T7 (BnR + CM compost) equivalent to 84.94 ppm N or 174.21 kg N ha^{-1} occurred during the sixth week of incubation. The net immobilization on T3 was very low compared to the others, amounting to 0.42 kg ha^{-1}.

Unlike the majority of reported N mineralization data[18–23], available N in this experiment fluctuated dramatically. Treatments involving the addition of composted banana residues combined with either chicken manure (T7), *Sesbania* (T6) or *Flemingia* (T4) effected a significant increase in available N during the second week of incubation and then declined during the fourth week of incubation. The fluctuation could be attributed to the characteristics of organic matter amendments. The sudden increase in available N of these treatments could be attributed to the presence of NH_4^+ or NO_3^- and easily degradable N compounds in the compost, which contribute directly to the mineral-N pool of the soil[23]. Such an increase would trigger higher microbial activity and higher N assimilation by microorganisms, thus immobilizing part of the mineral N pool at week 4. During this period, the increase in microbial activity would trigger competition for substrate, which would later caused microbial decay[24] and consequently release or re-mineralized the biomass N, thus increasing the available N during weeks 6–8. The

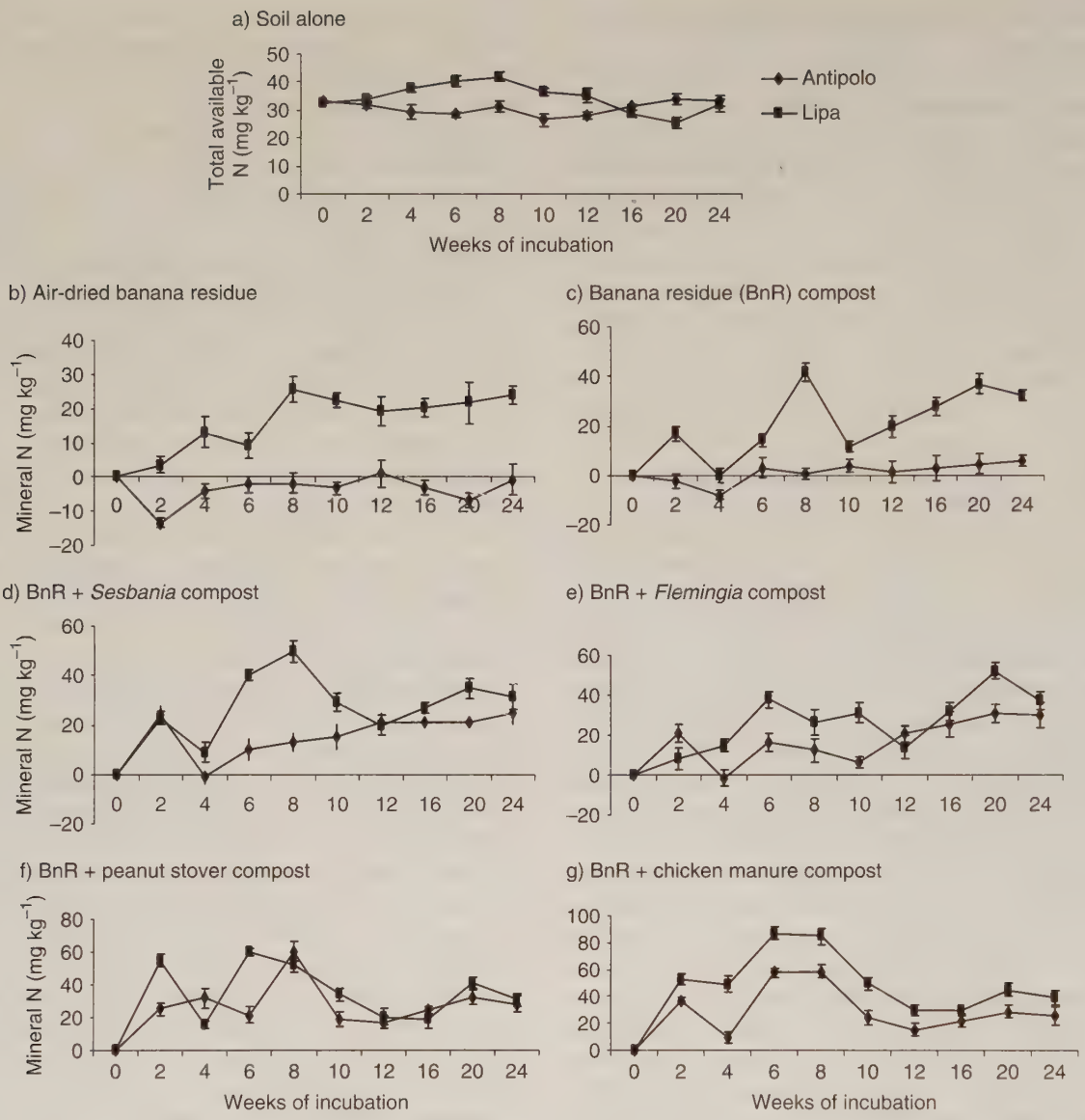

Figure 1. Available nitrogen (N) on unamended soil (a) and net nitrogen mineralization (b–g) of Antipolo and Lipa soils amended with different preparations of banana residue-based compost at 20 Mg ha^{-1}. Data points are means and standard errors from the three pots, LSD value at $P = 0.05$ is 20.30. (The scale of the horizontal axes is not linear.)

same phenomenon would explain the fluctuation of net available N in the soil until the system reached equilibrium, where net mineralization tended to level off. In the case of T7, T6, T5 and T4, this stage apparently started from week 12; for T3 it occurred as early as week 6 but at lower magnitudes of available N. These processes of mineralization–immobilization and re-mineralization occur simultaneously[25] and continuously until such time as equilibrium is reached.

Common characteristics of N availability dynamics in the two soil types are the more uniform and continuous increase of the available nitrogen beyond 10–12 weeks of incubation. After abrupt fluctuations during the early period of incubation, the available N in each treatment started to stabilize and increased gradually through time. Some of the treatments have dominant mineralization while others have immobilization occurring dominantly during the early phase of incubation. Net mineralization was observed beyond the twelfth week of incubation for the majority of soils amended with organic materials. This observation could be attributed to the immediate effect of organic materials on soil microflora and fauna and their coupled interaction.

Overall, the data show that higher nitrogen mineralization or nutrient supplying potential was observed in Lipa clay than in Antipolo clay. This observation could be attributed to the difference in soil pH. Lipa clay has moderately acid to slightly acid pH during the incubation period (data not shown), favoring higher microbial activity and a faster decomposition process, while the highly acidic nature of Antipolo clay creates an environment for lower microbial action. Higher microbial activity hastens the decomposition

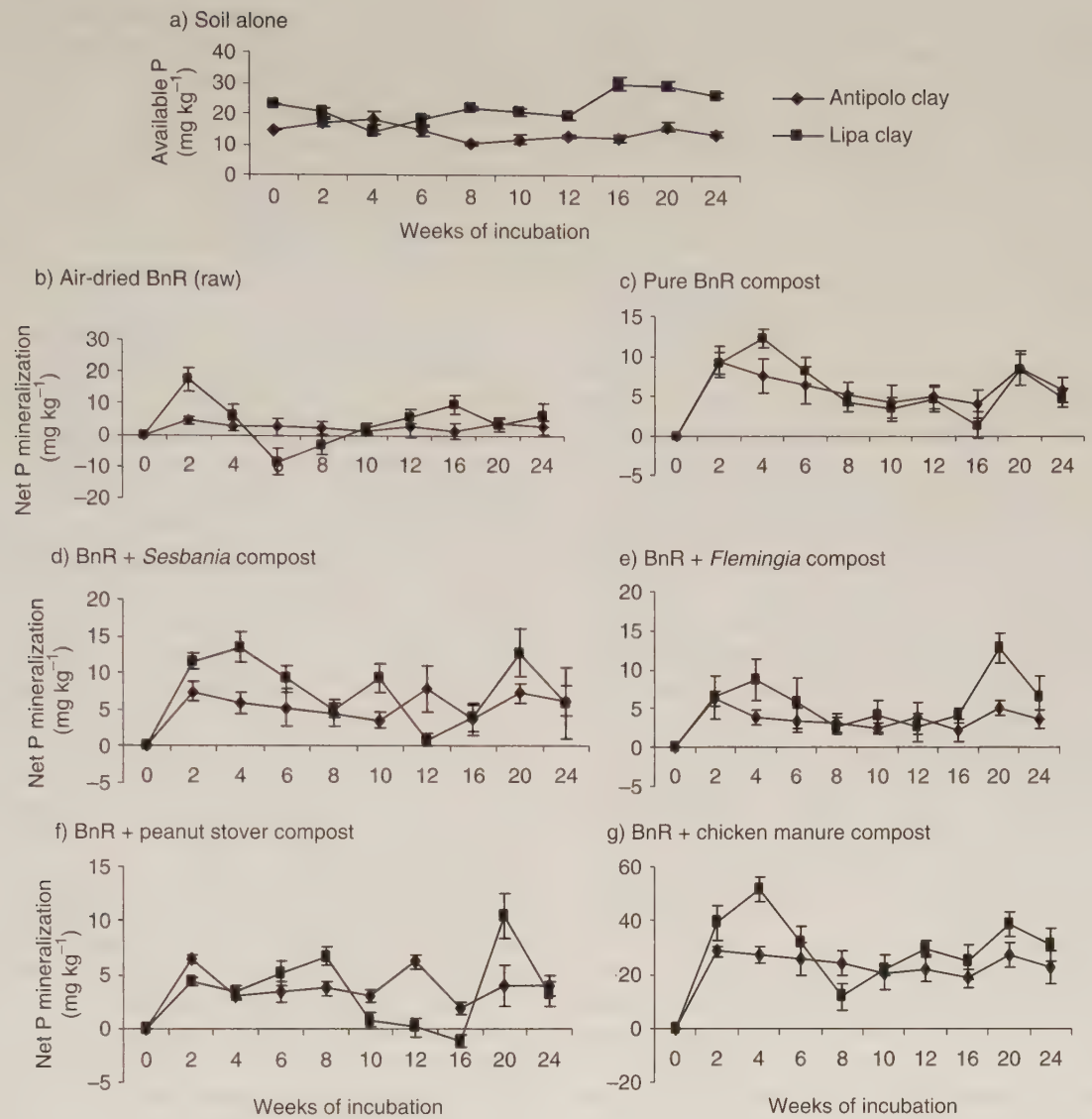
a) Soil alone
Available P (mg kg^{-1})
Antipolo clay
Lipa clay
Weeks of incubation
b) Air-dried BnR (raw)
c) Pure BnR compost
d) BnR + *Sesbania* compost
e) BnR + *Flemingia* compost
f) BnR + peanut stover compost
g) BnR + chicken manure compost
Net P mineralization (mg kg^{-1})
Weeks of incubation

Figure 2. Available phosphorus (P) in unamended soil (a) and net P mineralization (b–g) of Antipolo and Lipa soils as affected by different compost preparation amendments at 20 Mg ha^{-1}. Data points are means and standard errors from the three pots, LSD value at $P = 0.05$ is 8.68. (The scale of the horizontal axes is not linear.)

process, hence a faster release of nutrients from the organic materials[26].

Dynamics of phosphorus availability. The amounts of available P extracted by Bray P2 from the two soils with time of incubation are presented in Figure 2a. Antipolo soil had lower levels of available P (<5 mg kg^{-1}) that fluctuated very slightly within the 24-week incubation. Phosphorus deficiency is a characteristic of this extremely acid soil. At adequate levels of available P, greater fluctuations were observed in Lipa clay.

Based on the initial P analysis of Antipolo (1.7 mg kg^{-1}), the application of different organic materials at 20 Mg ha^{-1} resulted in considerable increase of available P concentration during the 24 weeks of incubation. Subtracting the initial available P concentration from the data throughout the incubation period revealed that all treatments involving organic matter amendments had net P mineralization in Antipolo clay (Figs 2b–g). Higher net mineralized P was observed in treatments containing banana residue combined with either chicken manure or legume compost (T3 to T7) as compared with air-dried banana residue (T2). However, the figure clearly shows that the increase in available P that occurred at 2 weeks generally leveled off until 24 weeks. It appears that phosphate fixation reactions prevailing in this extremely acidic[27,28] soil did not allow further build-up in available P (i.e., extractable by Bray P2 method).

In Lipa clay, higher available P was observed in T3, T4 and T6 during the second week and T5 on the fourth week of incubation. All these treatments had consistently higher available P than the initial amount (23 mg kg^{-1}) during the entire incubation period, indicating net P mineralization. In contrast to Antipolo clay, the application of air-dried BnR (Fig. 2b) and composted BnR+peanut stover (Fig. 2f) to Lipa clay resulted in net P immobilization during weeks

6–7 and 16, respectively. The higher immobilization rate in T2 (BnR compost) could be attributed to higher C/P ratio and lower P concentration of the material. In the case of T6, net P mineralization week 16 could be due to higher microbial demand for P during this period, resulting in net reduction of available P concentration.

Between the two soils, higher P mineralization was observed in Lipa clay than in Antipolo clay. Higher rates of net P mineralization in both soil types occurred during the early stage of incubation. The sudden increase of mineral P during the early period of incubation could be attributed to the dissolution of loosely stable phosphorus compounds due to the presence of organic acids in the composted organic materials[28]. Most investigators agree that the effect of organic matter on P availability is related to the action of microorganisms in decomposing organic materials and producing organic carbon compounds particularly effective in forming stable complex molecules with Fe and Al, and increased dissolution of calcium phosphate compounds[28]. In addition, the observed variable response between Antipolo clay and Lipa clay to compost amendments could be explained by one or more of the following: (1) the use of materials of wide C/P ratio, which can affect the kinetics of microbial immobilization and mobilization of inorganic P during the decomposition[29]; (2) the possibility that decomposition products such as organic acids and anions may have altered the availability of native soil P[28]; and (3) variable mineralization rates of resistant organic P compounds in the residue in the case of differences between soil types[30,31].

As described previously, the P content and the C/P ratio of the organic amendments used in the experiments varied considerably. In fact, composted banana residue + chicken manure had the highest P content and consequently the lowest C/P ratio among all treatments, while the air-dried banana residue had the lowest P content and a C/P ratio over 200. Tossah et al.[30] suggested that P immobilization occurs when the C/P ratio of the organic material added to soil exceeds 200. This certainly applies to the air-dried banana residue used in this study. On the other hand, it was also reported that residues with high total P content released more readily available P than residues with low total P content[32].

Dynamics of potassium availability. The amounts of exchangeable K in soils throughout incubation are presented in Figure 3. In unamended treatment (soil alone), Antipolo clay had a lower exchangeable K (extracted by 1 *N* ammonium acetate) than Lipa clay. Low exchangeable K concentrations are typical of extremely acidic old soils such as Antipolo clay[33]. Furthermore, the fluctuation of exchangeable K was minimal in Antipolo clay as compared to Lipa clay, but the fluctuations were not significantly different from respective initial concentrations. Unlike N and P, the exchangeable K in soil was insignificantly affected by the decomposition process. Potassium has low participation in microbial metabolism; its availability is not very sensitive to biochemical changes in the soil[13].

The application of different organic materials resulted in a significant increase of the exchangeable K (Fig. 3). Unlike nitrogen and phosphorus, an abrupt increase in exchangeable K was observed in all treatments 2 weeks after the incorporation of composts. This observation suggests that the potassium present on the organic materials became easily available upon incorporation into the soil. This could be attributed to the biochemical nature of potassium in plant material, which generally exists in ionic form[16].

Different compost preparations also resulted in changes at varying levels of exchangeable K. The application of pure banana residue (air-dried or composted) resulted in a significantly higher increase immediately, in the 2 weeks after incubation, as compared with the rest of the treatments. The incorporation of leguminous materials during composting has a dilution effect on the K-supplying capacity of the compost. The treatments involving *Sesbania* prunings, *Flemingia* prunings and peanut stover lowered the K content of compost, and consequently acted to reduce the contribution to the exchangeable K in the soil. The same effect was observed on the use of chicken manure, wherein the lower K content of the compost resulted in the lowest exchangeable K increment. Apparently, the magnitude of increase of exchangeable K in both soils was directly proportional to the increase in the quantity of K present in the compost materials.

NPK-supplying potential. The nutrient-supplying potential of the organic amendments was estimated from the maximum mineralization rate during the incubation period. The two soil types used in the experiment have different nutrient-supplying potentials, based on their native or indigenous nitrogen pool and the different formulation of banana residue composts. Indigenous N from Antipolo clay can supply available nitrogen up to 60 kg N ha^{-1} while Lipa clay can supply up to 83 kg N ha^{-1}. Considering the high-N composts (T4, T5, T6, T7), their contribution to the available nitrogen pool ranged from 55 to 122 kg N ha^{-1} for Antipolo clay and 58–155 kg N ha^{-1} for Lipa clay. In general, the application of composted BnR + chicken manure at 20 Mg ha^{-1} contributed the highest available N to the soils. This was followed by the application of composted BnR combined with peanut stover. The other compost materials (BnR + *Flemingia* and BnR + *Sesbania*) had more or less the same N-supplying potential.

In case of the P-supplying potential, native P in Antipolo clay could supply up to 36 kg P ha^{-1}, while Lipa clay supplied 60 kg P ha^{-1}. The contribution of the compost amendments to available P was very minimal in Antipolo clay, ranging from 9 to 57 kg P ha^{-1}, while in Lipa clay, it ranged from 9 to 78 kg P ha^{-1}. All the upper values were due to the application of BnR + chicken manure compost.

Comparing the relative K-supplying capacity (net increase in exchangeable K) of the compost preparations among the two soil types, a generally higher magnitude of increase was observed in Antipolo than in Lipa clay.

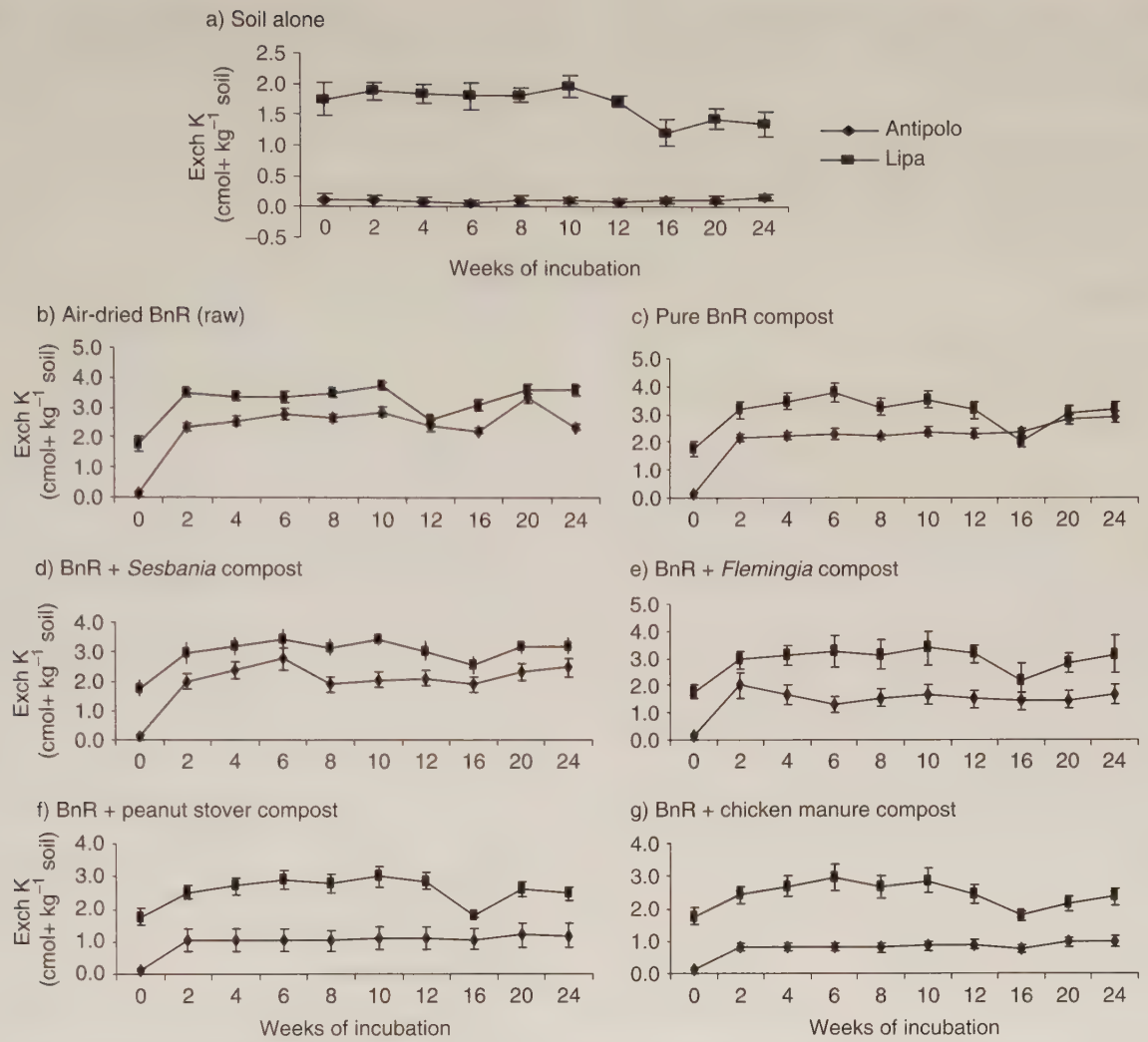

Figure 3. Exchangeable potassium (Exch K) of Antipolo and Lipa soils as affected by different compost preparation amendments at 20 Mg ha^{-1}. Data points are means and standard errors from the three pots, LSD value at $P = 0.05$ is 0.51. (The scale of the horizontal axes is not linear.)

Averaging each treatment across time, higher increments were obtained from the application of compost in Antipolo (679–1954 kg K ha^{-1}) than in Lipa (16–1255 kg ha^{-1}). All the upper values observed were due to the application of air-dried banana residue.

Conclusions

In response to the high demand for organic bananas in the global market, a surge in organic banana production is expected. Unfortunately, research on organic production systems in the Philippines is minimal. This study was conducted to generate quantitative information on the potential of banana residue as a source of nutrients for the establishment of organic banana farms. Based on these results, the utilization of leguminous materials, such as *Sesbania* and *Flemingia* prunings and peanut stover, in combination with banana residues improved the nitrogen content of banana-residue compost and enhanced the decomposition process. Utilization of chicken manure during composting improved both N and P contents of the final product. Bioquick was observed to be more beneficial as a composting inoculant if used in the presence of materials containing high levels of nitrogen; notably, Bioquick alone has a minimal effect in hastening the decomposition of banana residue. Apart from contributing to compost quality, the inclusion of high-N-containing materials, such as leguminous plant residues, could shorten composting to 4–8 weeks. With banana residue + chicken manure, 4-week composting could be sufficient.

Overall, our results showed that banana residues have great potential to supply the potassium requirements for banana plantations. However, inclusion of leguminous materials and/or chicken manure will be necessary to meet the nitrogen and phosphorus requirements of the farms. Based on the existing fertilization rate of banana plantations in the Philippines[6,7] of 800–1200 kg N ha^{-1}, 200–300 kg P_2O_5 ha^{-1}, 1600–1800 kg K_2O ha^{-1}, mineralization data indicated that 20 Mg ha^{-1} of banana residues mixed with leguminous materials or chicken manure could

supply up to 20–50% of the N and P demand for a banana plantation, while full K requirements could be provided by these compost preparations.

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Plant Parasitic Nematodes in Subtropical and Tropical Agriculture, 2nd Edition

Edited by M Luc, formerly of ORSTOM, France; R Sikora, University of Bonn, Germany; J Bridge, CABI Bioscience, Egham, Surrey, UK

March 2005 896 pages
HB 0 85199 727 9 £99.50 (US$195.00)

Readership

Students and researchers in crop protection and plant nematology.

Key Features

- The definitive global reference work on its subject
- A book that combines theory and practice, concentrating on nematode species that lower crop yields
- Includes fully revised chapters, contributions from many new authors, and an extended number of illustrations

Main Description

This book examines all aspects of practical plant nematology in subtropical and tropical agriculture. The second edition has been fully revised and updated to take into consideration developments that have taken place since the publication of the first edition in 1990. It covers all the major food and cash crops that are of economic significance in the tropics and subtropics. It provides practical guidance on methods of extraction, processing and diagnosis of different plant and soil nematodes and on integrated pest management. The information in this book is supported by abundant illustrations, including 128 colour photographs.

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Irrigation and Drainage Performance Assessment: Practical Guidelines

by M G Bos, International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands, M A Burton, ITAD-Water, Hassocks, UK and D J Molden, International Water Management Institute, Colombo, Sri Lanka

February 2005 176 pages
HB 0 85199 967 0 £40.00 (US$75.00)

Readership

Professionals, researchers and students in water management, irrigation, drainage, soils and agricultural engineering

Key Features

- Addresses a critical issue in contemporary water management
- Is unique in its focus on performance assessment

Main Description

Effective irrigation and drainage systems are essential if growing demands for water resources are to be met. For the use of water for irrigation to be improved we must understand current levels of performance. This book draws together the growing body of knowledge on irrigation and drainage performance assessment that has been gained over the last twenty years. It provides guidelines for practitioners to enable them to design and carry out performance assessment and implement performance-based management. Developed by a working group of the International Commission on Irrigation and Drainage (ICID) it provides a generic framework for performance assessment with guidance on the theory and practice of how to audit and assess the performance of irrigation and drainage schemes.

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2. Brink, R.H. Jr, Dubach, P., and Lynch, D.I., 1960. Measurement of carbohydrates in soil hydrolyzates with anthrone. Soil Science 89:157–166.
3. Greenland, D.J., and Szabolcs, I., (eds). 1994. Soil Resilience and Sustainable Land Use. CAB International, Wallingford, UK.
4. Arshad, M.A. and Coen, G.M., 1992. Characterization of soil quality: Physical and chemical criteria. American Journal of Alternative Agriculture 7:25–31.
5. Coale, F.J. 1996. Descriptions of the soil test interpretive categories used by the University of Maryland Soil Testing Laboratory. SFM-3. University of Maryland, College Park.

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